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Analysis of the Variation of Horizontal Stresses and Strains in Bedded Deposits in the Eastern and Midwestern United States

by

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Thesis submitted to the College of Engineering and Mineral Resources
West Virginia University
In partial fulfillment of the requirements for a degree of

Master of Science
in
Mining Engineering

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Morgantown, West Virginia

2004

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ABSTRACT

The variation of the horizontal stress magnitude in bedded deposits in the eastern and Midwestern United States is analyzed with respect to the site depth and the rock elastic modulus using data from 40 sites. For the development of adequate regression models with the elastic modulus, zones with sufficiently uniform strains must be established. A low strain zone encompassing much of the eastern United States and a high strain zone encompassing a portion of southern West Virginia are delineated. In each zone, the regression models with the elastic modulus as the independent variable explains about 85 percent of the maximum horizontal stress variation. In general, the minimum horizontal stress is much less dependent on the elastic modulus. Though the site depths range from 275 to 2,300 ft, depth can explain only 15 percent of the maximum horizontal stress variation and is apparently not a significant independent factor.

DEDICATION

I dedicate this thesis to my dad who always provided encouragement for me to continue my education but did not see the completion of this work.

Stanley F. Dolinar

1915 to 2003

ACKNOWLEDGEMENTS

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ABBREVIATIONS OF UNITS

ft-feet
psi- pounds per square inch

CHAPTER 1: INTRODUCTION

The objective of this study is to analyze the variation of the horizontal stress and strain with respect to the elastic modulus of the rock and the depth of the measurement from the surface of the earth based on stress measurements made in mines in bedded deposits in the eastern and Midwestern United States. At the mining depths in coal and limestone deposits, the maximum horizontal stress, generally, exceeds the vertical stress often by several times. Further, the horizontal stress has been linked to ground control problems in a number of mines in both coal and limestone. Therefore, the magnitude of the horizontal stress is an important ground control issue as are the factors that may affect the magnitude of the horizontal stress. Two primary factors that in general influence the magnitude of the horizontal stress are the elastic modulus of the rock and the depth.

Therefore, horizontal stresses measured in the eastern and Midwestern United States are examined to determine if there is any general relationship between the elastic modulus and horizontal stress magnitude. Elastic theory specifies the relationship between the stress and the strain at a point, as the elastic modulus. This study will investigate if there is a relationship between the elastic modulus and the horizontal stress magnitude across larger geographic areas. If such relationships are developed, the implication is that those sets of stress measurements are under a similar or uniform strain field.

Besides the stresses, the horizontal strains are also evaluated. Essentially, this removes the elastic properties of the rock as a factor in a given analysis. Therefore, other factors such as depth can be examined without the influence of the rock properties. The horizontal strains can also be examined for geographic variation and to determine how consistent or variable the strain field is across the eastern and Midwestern United States. The strain field in combination with the elastic properties will determine the magnitude of the horizontal stress.

The effects of depth on the magnitude of the horizontal stress are considered to determine if a general depth factor for the horizontal stress exists and if it does, the magnitude of that depth factor. Essentially, does the magnitude of the horizontal stress increase with depth, and to what degree.

This study uses the available horizontal stress measurement and elastic property data from mines in sedimentary deposits in the eastern and Midwestern United States. However, such an analysis requires data from the individual stress measurements and the elastic properties of the rock associated with those measurements. This data criterion limits the amount of published stress data that can be used. Initially, the measurements made in the Beckley coalfield are evaluated where an extensive stress measurement program was conducted with the elastic properties of the individual stress measurements and site depths available. Further, an analysis is then conducted based on other stress measurements in the northern and central Appalachian regions and the eastern Mid-Continent region that includes the Illinois basin.

CHAPTER 2: REVIEW OF LITERATURE

In the United Kingdom, the variation in the magnitude of the maximum horizontal stress measured in coal mines can be explained to a high degree by the elastic modulus of the rock and the Poisson's ratio effect from the vertical stress due to gravity (Cartwright 1997). A general model using a multiple correlation analysis was developed for the coal measure rocks in both England and the United Kingdom that shows a strong relationship between the maximum horizontal stress magnitude and the elastic modulus and Poisson's effect from gravity. The multiple correlation coefficient for the United Kingdom as a whole was 0.94 and for England only, 0.95. The high correlation in these models indicates that the coalfields in England are subjected to essentially the same uniform horizontal strain field. Further, the increase in the maximum horizontal stress with depth can be explained by the vertical stress from gravity and Poisson's effect. However, the correlation between the elastic modulus and the minimum horizontal stress was much weaker (Bigby et al., 1995). The multiple correlation coefficient was for the United Kingdom 0.55 and for England 0.41. The relationships were weak enough not to be used to estimate the minimum stress. In the United Kingdom study, the depths of the measurements ranged from 300 to 3,500 ft. Therefore, the analysis covers a range in depth applicable to mining. In the English model, the maximum horizontal stress has a tectonic strain component above the gravity affects that ranges between 700 and 800 micro strains. The minimum horizontal stress has a tectonic strain component without gravity that ranges between 30 and 100 micro strains. These tectonic strains are the coefficients for the elastic modulus in the models.

Further, evidence of a relationship between the magnitude of the maximum horizontal stress and the elastic properties at specific sites in the United States have been reported (Hanna et al., 1991, Aggson and Mouyard, 1988A and 1988B). In evaluating horizontal stresses measured in the roof of a coal mine in the Illinois basin, Hanna et al., (1991) stated that "the magnitude of the major principal stress is related linearly to the elastic modulus of the roof rock." Aggson and Mouyard (1988A and 1988B) reported a linear relationship between the elastic modulus and the maximum horizontal stress magnitude for a mine in West Virginia. A relationship between the maximum stress and

the elastic modulus of the rock has also been shown to exist in China (Guangyu et al., 1986). The explanation given was that a rock mass with a higher elastic modulus accumulates higher elastic strain energy when subjected to the same strain field. This implies the strain field was uniform where the measurements were made. Therefore, there is evidence that the elastic modulus of the rock is an important factor in the variation of the magnitude of at least the maximum horizontal stress.

A theoretical model has also been developed that provides an estimate of the mean horizontal stress based on gravity and Poisson's effect and a thermal gradient component that also involves the elastic constants (Sheorey et al., 2002). There appears to be a reasonable good fit between this model and stress data for North America though the analysis is based on measurements made prior to 1980. It is also stated that the equation shows the horizontal stress has a definite dependence on the elastic modulus. Based on the thermal coefficient and gradient provided in the report, the coefficient for the elastic modulus is 240 micro strains at the surface, 313 micro strains at 1,000 ft and 386 micro strains at 2,500 ft. However, the model is not adequate where there is a strong influence of topography, major geologic features or tectonics.

The increase in horizontal stress with depth in North America has been evaluated by a number of authors (Brown and Hoek, 1978; Herget, 1986; Mark and Mucho, 1994). The studies by Herget (1986) and Brown and Hoek (1978) were conducted based on measurements primarily from igneous and metamorphic rocks while the measurements presented by Mark and Mucho (1994) were from coal measure rocks. Herget (1986) found the magnitude of the average horizontal stress increased by about 2.56 psi/ft for the depth range from 0 to 2,600 ft while from Brown and Hoek's (1978) analysis the increase ranged from 0.35 to 0.61 psi/ft of depth. The study by Mark and Mucho (1994) indicates that the maximum horizontal stress increases with depth in coal measure rocks. Although no analysis was conducted on the data, from the graphical presentation, the maximum horizontal stress magnitude appears to be increasing faster than the vertical stress. More recently, Mark et al. (2001), has given the increase in depth for coal mines in the eastern United States in the form of regression equations, one linear and the other logarithmic. The linear increase in the maximum horizontal stress with depth is 1.23 psi/ft while the logarithmic equation gives a similar increase between 500 and 1,500 ft.

Except for the data presented by Herget (1986) from the Canadian Shield, the correlation between depth and the horizontal stress for these models is in general poor. Further, based on stress measurements in the United Kingdom, the following statement was made "Unlike the vertical stress, the horizontal stress component is not related to depth but to the rock stiffness" (Hayes et al., 1995). Therefore, the effects of depth on the maximum horizontal stress are reexamined not only based on the stress but the elastic strain. For the depth, the strain data needs to be evaluated because of potential effects of the elastic properties on the stress magnitude.

There is a theoretical basis for the increase of the horizontal stress with depth that develops from the gravity load and Poisson's ratio (Obert and Duvall, 1967; Jaeger and Cook, 1969). Both Sheorey et al. (2002), and Cartwright (1997) include this as a depth factor in their models for estimating the horizontal stress. The increase with gravity is also indicated in the calculation of what is termed the excess or tectonic horizontal stress, the horizontal stress in excess of the expected gravity load (Aggson, 1979A; Bickel, 1993).

CHAPTER 3: MODEL TYPES AND STRESS MEASUREMENTS USED IN THE STUDY

3.1 MODELS USED TO ANALYZE THE STRESS VARIATION

To analyze the variation of the horizontal stress magnitude with respect to the elastic modulus and the depth, several models are used. A regression analysis on the data is conducted to develop the models and to examine how well the models explain the data variation.

For the relationship between the horizontal stress magnitude and the elastic modulus, the following type of equation is used

$$P, Q = K_1 E + K_2 \tag{3.1}$$

where   P   =   maximum horizontal stress, psi,

        Q   =   minimum horizontal stress, psi,

        K_1 =   strain coefficient for either the maximum or minimum horizontal stress, micro strain,

        E   =   elastic modulus, 10^6 psi,

and K_2 =   constant for either the maximum or minimum horizontal stress, psi.

The coefficient K_1 is directly related to the strains while the K_2 constant is related to other factors that cause an offset in the stress-strain relationship such as the depth or thermally induced strains (Cartwright, 1997; Herget, 1988). A large constant can also result from measurements obtained from a non-uniform strain field where there can also be a different distribution of the elastic modulus that was sampled within those strain fields.

In general, as previously noted, the horizontal stress magnitude does appear to increase with depth. There are at least two aspects to this increase, the change from an increase in the vertical stress, and the change in the excess or tectonic component of the horizontal stress. There are also other potential factors that may cause an increase in the horizontal stress magnitude that may be related to depth such as increases due to thermal

effects (Sheorey, 1994). In theory, based on plane strain conditions, the horizontal stress from depth and gravity is given by the following equation (Jaeger and Cook, 1969)

$$P_v = 1.1 \, [v/(1-v)] \, D \qquad\qquad (3.2)$$

where P_v = horizontal stress due to depth, psi,

v = Poisson's ratio,

and D = depth, ft.

Based on the average rock density for sedimentary rock, the vertical stress is assumed to increase by about 1.1 psi/ft of depth.

Equation 3.2 can be used to estimate the contribution of the vertical stress or depth to the measured horizontal stress. Subtracting the gravity effects from the measured horizontal stress will result in the excess stress. The following equations give the excess horizontal stress (Aggson, 1979A; Bickel, 1993)

$$P_e = P-1.1 \, [v/(1-v)] \, D \qquad\qquad (3.3a)$$
$$\text{and}$$
$$Q_e = Q - 1.1 \, [v/(1-v)] \, D \qquad\qquad (3.3b)$$

where P_e = maximum excess horizontal stress, psi,

and Q_e = minimum excess horizontal stress, psi.

Essentially, the excess stress is the component of the horizontal stress that exceeds that due to gravity.

The following equation is used to examine the relationship between the elastic modulus and the excess stress

$$P_e, Q_e = K_1 E + K_2. \qquad\qquad (3.4)$$

As previously discussed, the constant K_2 in equation 3.4 can be related to possible thermally induced strains or other unknown factors that may systematically influence the horizontal stresses. This constant can also result from non-uniform strain fields where the stress does not vary linearly with the elastic modulus. If the constant K_2 is sufficiently small, the following equation can be used

$$P_e, Q_e = K_1E. \qquad (3.5)$$

A part or most of the excess stress may be tectonic in origin. The tectonic stresses being related or developed from the forces that generate plate tectonics (Zoback and Zoback, 1989; Zoback, 1992; Mark and Mucho, 1994). Because a large component of the excess horizontal stress is probably due to tectonics, this component is often referred to as the tectonic stress (Mark and Mucho, 1994; Cartwright, 1997). The portion of the stress field that is influenced by the elastic modulus has been taken to be the tectonic portion of the stress field (Cartwright, 1997). This implies that the tectonic stresses are the result of the coefficient K_1 in equations 3.4 and 3.5 where this coefficient can be considered related to the tectonic strain. However, in discussions in this paper such stresses and strains above the gravity load will be in general referred to as excess rather than tectonic.

Strains from the maximum and minimum measured and excess horizontal stresses can also be evaluated. These strains are calculated from the following type of equations

$$\varepsilon_p, \varepsilon_q = P,Q/E \qquad (3.6a)$$
$$\text{and}$$
$$\varepsilon_{pe}, \varepsilon_{qe} = P_e,Q_e/E \qquad (3.6b)$$

where ε_p = strain from the maximum horizontal stress, micro strain,

ε_q = strain from the minimum horizontal stress, micro strain,

ε_{pe} = strain from the maximum excess horizontal stress, micro strain,

and ε_{qe} = strain from the minimum excess horizontal stress, micro strain.

These calculated strains are referred to as the strains resulting from the maximum or minimum horizontal or excess stress. These are not the actual strains that would be measured at a point since those strains involve the complete stress field and not just a stress component. The excess or tectonic strain calculated in equation 3.6 is related to the K_1 coefficient of equation 3.5. With equation 3.6, the strains from the maximum horizontal stress for individual measurements are calculated while for equation 3.5, the coefficient is the average strain from the maximum horizontal stress based on a regression analysis from several measurements. Further, the strains developed from these equations can also be referred to as maximum and minimum horizontal stresses normalized by the elastic modulus of the rock.

The depth factor can be evaluated through an equation of the following type

$$P = K_D D + P_s \qquad (3.7)$$

where K_D = depth factor, psi/ft,
and P_s = maximum horizontal stress at the surface, psi.

The maximum horizontal stress at the surface is the excess or tectonic stress.

Equations that combined both depth and the elastic properties can be developed through a multiple regression analysis. These equations have the following form

$$P, Q = K_D D + K_1 E + K_3 \qquad (3.8)$$

where K_3 = constant, psi.

Finally, the following type of equation is used to evaluate the effects of depth on the strain

$$\varepsilon_p = K_{ND} D + \varepsilon_s \qquad (3.9)$$

where K_{ND} = normalized depth factor, micro strain/ft,

and ε_s = strain from the maximum horizontal stress at the surface, micro strain.

Essentially, this equation eliminates the variation of the elastic properties between measurements thus allowing for a comparison between the horizontal stress or strain and depth that is not masked by the elastic properties.

3.2 STRESS MEASUREMENTS USED IN ANALYSIS

Stress measurements used in this analysis were determined by two techniques, these were overcoring of either the USBM (United States Bureau of Mines) borehole deformation gage or the CSIRO (Commonwealth Scientific and Industrial Organization of Australia) Hollow Inclusion (HI) cell and hydraulic fracturing stress measurements. The general criteria for using stress data were that both the depth of the site and the elastic properties of the rock were required before a measurement could be used in the analysis. With the USBM borehole deformation gage and hydraulic fracturing, the horizontal stresses can be determined in vertically drilled holes either in the roof or floor of the mine. With the CSIRO HI-cell, the complete 3-dimensional stress is determined and the cell can be placed in any hole orientation to obtain the horizontal stress. All the measurements used in this analysis were obtained from underground test sites.

The technique to measure the stresses with the USBM borehole deformation gage and overcoring are well documented (Bickel, 1985, 1993). The result of an overcoring measurement is the determination of the two dimensional stress in the plane of the measurement. The elastic properties for the overcore are usually determined using a biaxial test of the core and are normally determined for each stress measurement. Several measurements are usually obtained from one hole at a site with the measurements being averaged to determine a site stress (Duval and Aggson, 1980). In general, for the analysis, if the elastic properties for a given overcoring measurement were not determined the measurement was not used though there are some exceptions. All except two of the site stresses were determined using this method.

The CSIRO HI-cell is also overcored and will result in the determination of the 3-dimensional stress field. Again, the installation and use of the cell are well reported (International Society of Rock Mechanics, 1987; Wortrucki and Walton, 1976). From the

three-dimensional stress, the principal stresses in the horizontal plane can be calculated. The elastic properties are obtained by testing the individual overcores.

The hydraulic fracturing technique is also well documented though in this case the underground data was obtained using specially designed equipment (Oyler, 2001). Again, information on the elastic properties was required. However, the elastic properties are not necessary to calculate stresses with this method and must be determined by other methods such as from laboratory testing of core obtained from the tested formation. Measured stresses may be reported from individual tests, as an average stress for several tests or as a range of values from all the tests.

CHAPTER 4: HORIZONTAL STRESS MEASUREMENTS FROM SITES IN THE EASTERN UNITED STATES

Figure 4-1 shows the site locations of the stress measurements used in this analysis from the eastern and Midwestern United States. The measurements from forty sites are grouped into three main regions. These are the northern and central Appalachian regions and the eastern Mid-Continent region. In this section, the stress measurements, site depth and elastic modulus of the rock as well as the horizontal strains from the maximum and minimum stresses that will be used in the analysis are presented.
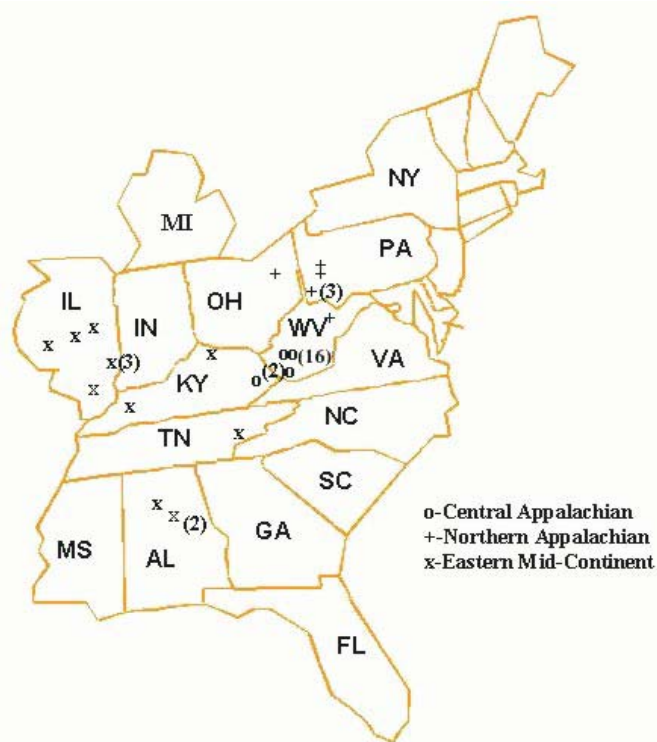
**Figure 4-1. Location of stress measurement sites used in study.
Numbers in parentheses indicates multiple sites in close proximity.**

4.1 CENTRAL APPALACHIAN REGION

This region encompasses sites from southern West Virginia and eastern Kentucky. Stress measurements were available from 15 sites in the Beckley seam, one site in the Sewell seam, two sites in the Pocahontas #4 seam and one site in the Eagle seam in southern West Virginia as well as one site in the Elkhorn #3 seam in eastern Kentucky.

Measurements at these sites were made using the USBM borehole deformation gage and overcoring technique. The results of the individual stress measurements including: the maximum and minimum measured and excess horizontal stress, the elastic modulus and the resulting strains are given in Appendix A, table A-1 and A-2 for the Beckley coalfield and in Appendix B, table B-1 for other sites in the central Appalachian region. Table 4-1 shows a summary of the horizontal stress, stress direction, elastic modulus and depth for each site.

Table 4-1. Summary of horizontal stresses by site in the central Appalachian region.

Site	Seam	Horizontal stress			Excess stress, psi		Elastic modulus, 10^6 psi	Depth, ft
		Maximum, psi	Minimum, psi	Direction of maximum	Maximum	Minimum		
Beckley #4, hole 1	Sewell	1484	1141	N 25 °W	1183	840	1.77	820
Beckley#1, hole 2	Beckley	3172	1890	N 75 °E	2758	1476	6.77	1130
Beckley #2, hole 3	Beckley	2308	1677	N 52 °W	1905	1274	2.26	1100
Bonny, hole 4	Beckley	3180	3038	N 54 °E	2763	2621	3.59	1136
Bonny, hole 5	Beckley	6109	3326	N 57 °E	5688	2905	6	1148
Maple Meadows, hole 6	Beckley	2730	2656	N 46 °W	2470	2396	6.32	708
Maple Meadows, hole 7	Beckley	4476	3240	N 63 °E	4207	2971	4.44	735
Maple Meadows, hole 8	Beckley	4258	2362	N 69 °E	3882	1986	7.09	1025
Maple Meadows, hole 9	Beckley	3188	2354	N 71 °E	2890	2056	2.46	814
Maple Meadows, hole 10	Beckley	3326	1657	N 54 °E	3030	1361	6.92	807
Beckley Mining, hole 11	Beckley	3095	2508	N 54 °E	2860	2273	2.95	640
Beckley Mining, hole 12	Beckley	3703	2902	N 71 °E	3384	2583	2.94	870
Beckley Mining, hole 13	Beckley	3124	2331	N 59 °E	2831	2038	2.7	800
Beckley Mining, hole 14	Beckley	3765	2280	N 55 °E	3384	1899	3.5	1040
Beckley #1, hole 15	Beckley	3199	1768	N 69 °E	2942	1511	7.32	700
Beckley #2, hole 16	Beckley	1800	1346	N 42 °W	1672	1218	1.72	350
Eagle seam mine	Eagle	1760	1370	N 49 °E	1430	1040	2.95	900
Hendrix mine	Elkhorn #3	2254	1802	N 65 °E	2052	1600	5.24	550
Olga mine, site 1	Pocahontas #4	3300	2400	N 62 °E	2713	1813	3.59	1600
Olga mine, site 2	Pocahontas #4	3000	1900	N 61 °E	2542	1442	3.25	1250

4.1.1 Beckley Coalfield

The Beckley coalfield is located about 10 miles west-northwest of Beckley, West Virginia. Mines in the area have had considerable ground control problems related to the horizontal stress (Aggson, 1978, 1979A; Dolinar et al., 1982; Agaptio et al., 1980; Agapito and Gilbride, 2002). As a result of the stress related ground control problems, an extensive horizontal stress measurement program was conducted in the Beckley coalfield in the late 1970's and early 1980's (Aggson, 1978; Agapito et al., 1980). Stress measurements were made at a total of 16 sites in 6 mines. The data set contains 61 individual stress measurements obtained in sixteen holes drilled in the mine roofs. Fifteen sites were in the Beckley coal seam and one site in the overlying Sewell seam.
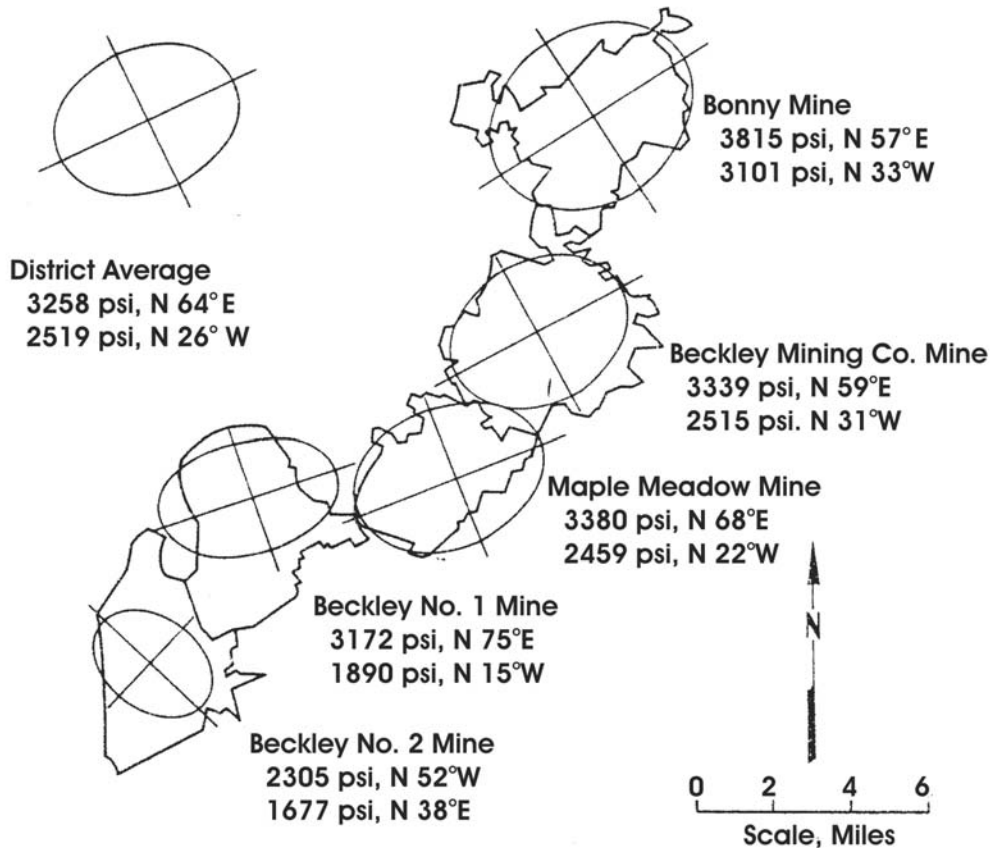
Figure 4-2. Average mine and district horizontal stresses measured in the Beckley seam (modified from Agapito et al., 1980A).

Figure 4-2 shows a map of the mines in the Beckley seam and the average horizontal stresses measured in each mine. The average for the district is also shown

(Agapito, et al., 1980A). The measurements extend for a distance of about 25 miles with the depth of the sites ranging from 350 to 1,148 ft. In general, the Beckley coalfield is subjected to a horizontal stress that is substantially higher than the expected vertical stress at these depths where the maximum horizontal stress by site varies from 1,484 to 6,109 psi. The direction of the maximum horizontal stress is from the northeast except in the Beckley #2 Mine, and in the Beckley #4 Mine in the Sewell seam where the directions are from the northwest. One site in the Maple Meadows Mine also has a maximum horizontal stress from the northwest, however, the stresses at the site are nearly hydrostatic. In general, from the Beckley #1 Mine to the Bonny Mine, both the maximum and minimum horizontal stress magnitudes increase in the northeast direction.

Across the coalfield based on the site measurements, the elastic modulus ranges from 1.77 to 7.32 million psi. The strain from the maximum horizontal stress ranges from 432 to 1,296 micro strains and from the minimum horizontal stress from 242 to 987 micro strains. Clearly, there is a substantial range in both the elastic modulus and in the strains.

4.1.2 Olga Mine, Pocahontas #4 Seam

The mine is located in McDowell county West Virginia in the Pocahontas #4 seam about 25 miles southwest of the Beckley seam study area (Campoli et al., 1990). Measurements were made at two sites in the mine with the overburden depths of 1,250 and 1,600 ft. However, for the analysis, the measurements at 5.8 ft at the 1,600 ft site and from 2.3 to 6.6 ft at the 1,250 ft site were not used because the measurements were relatively close to the opening and deeper measurements were available. At the two sites, for the measurements used in the analysis, the site strains from the maximum horizontal stress are 919 and 923 micro strains and from the minimum horizontal stress 585 and 668 micro strains. The site elastic modulus is 3.25 million psi for the 1,250 ft site and 3.59 million psi for the 1,600 ft site.

4.1.3 Mine, Eagle Seam

The mine is located in Raleigh county West Virginia about 10 miles northwest of the Beckley seam study area. The measurements were made in the Eagle seam with a site

depth of 900 ft. The site strain from the maximum horizontal stress is 597 micro strains and from the minimum horizontal stress, 464 micro strains. The site elastic modulus is 2.95 million psi.

4.1.4 Hendrix Mine, Elkhorn #3 Seam

The mine is located in Letcher County in southeastern Kentucky in the Elkhorn #3 seam. The measurements were made in shale in the mine roof (Wright et al., 1979; Unrug et al., 1984). The deepest three measurements ranging from 13.7 to 23.4 feet in the mine roof were used to calculate the horizontal stress. Because of delamination of the large diameter overcores, elastic properties had to be determined from small diameter core drilled from the larger cores. The elastic properties used were those determined in the direction parallel to the bedding. One elastic modulus, 5.24 million psi was used to determine the stresses from the three measurements. The maximum and minimum horizontal strains from those stress components are 430 and 343 micro strains. The site depth was 550 ft.

4.1.5 Summary of Central Appalachian Region

The central Appalachian region includes measurements from southern West Virginia, and eastern Kentucky. Stress measurements used in the analysis were obtained from the Beckley, Sewell, Pocahontas #4, Eagle and Elkhorn #3 seams. In general, the Beckley seam dominates the data because of the number of sites. There is a substantial range of strains over the region with the average site strains from the maximum horizontal stress varying from 432 to 1,296 micro strains and the strains from the minimum horizontal stress varying from 242 to 987 micro strains. The sites are located in mountainous topography with the depth ranging from 350 to 1,600 ft. The site elastic modulus varies from 1.77 to 7.32 million psi.

4.2 NORTHERN APPALACHIAN REGION

For this study, the northern Appalachian region encompasses parts of eastern Ohio, northern West Virginia and western Pennsylvania. Table 4-2 shows the horizontal stresses for each site. A summary of the individual measurements used in the analysis

including the maximum and minimum horizontal stress, the maximum and minimum excess horizontal stress, the elastic modulus and the resulting strains are given in Appendix C, table C-1.

Table 4-2. Summary of horizontal stresses by site for the northern Appalachian region.

Site	Seam/ formation	Horizontal stress			Excess stress, psi		Elastic Modulus, 10^6 psi	Depth, ft
		Maximum, psi	Minimum, psi	Direction of maximum	Maximum	Minimum		
Tanoma, PA	Lower Kittanning	3335	2787	N 87 °E	3071	2523	5.8	720
Phillippi WV	Lower Kittanning	3014	2265	N 75 °E	2812	2063	4.29	550
Fayette County, PA	Loyalhanna	6910	3975	N 71 °E	6763	3828	11.2	400
Barberton, OH	Columbus	5500	4000	E	4657	3157	9	2300
Southwest, PA, site 1	Pittsburgh	1324	1024	N 32 °E	1177	877	1.8	400
Southwest, PA, site 2	Pittsburgh	2370	2260	N 78 °E	2113	2003	4.4	700
Southwest, PA, site3	Pittsburgh	3080	2180	N 70 °E	2787	1887	7.65	800

4.2.1 Loyalhanna Limestone Formation

Horizontal stress measurements were made in a limestone mine in the Loyalhanna Limestone in Fayette County, Pennsylvania. This mine has had a history of roof falls many of which are related to the horizontal stress (Iannacchione et al., 1997, 2002). The stress measurements were made in the roof and floor using the hydraulic fracturing technique (Oyler, 2001). The depth of the site was 400 ft.

Table 4-3 shows the horizontal stress measured at a given depth in the roof and floor. An average horizontal stress is also given for the site. Based on a Poisson's ratio of 0.25 and the average horizontal stress at the site, the excess stresses were calculated as $P_e = 6,765$ psi and $Q_e = 3,830$ psi.

An elastic modulus for the site was determined from testing of vertically drilled core from another nearby limestone mine in the same formation. The range in the elastic modulus was 8.5 to 14.2 million psi with an average of 11.2 million psi. This average is based on 12 specimens obtained from through out the Loyalhanna formation. Using the

average elastic modulus of 11.2 million psi, the strains from the average maximum and minimum horizontal stresses are 617 and 355 micro strains.

Table 4-3. Horizontal stresses in the Loyalhanna formation, Fayette County, PA

Location	Depth of measurement, ft	Horizontal stress		
		Maximum, psi	Minimum, psi	Direction of maximum
Roof	10.5	7200	4456	N 76 °E
Roof	11.5	6117	3145	N 76 °E
Average		6659	3800	N 76 °E
Floor	10	5800	3319	N 66 °E
Floor	11	8524	4993	N 66 °E
Average		7162	4150	N 66 °E
Average		6910	3975	N 71 °E

4.2.2 Columbus Limestone

Stress measurements were made at a limestone mine near Barberton, Ohio using the USBM borehole deformation gage and overcoring technique (Obert, 1962). The site was in the Columbus Limestone at a depth of 2,300 ft. The measured horizontal stresses at the site were P = 5,500 psi and Q = 4,000 psi. Using a Poisson's ratio of 0.25, the excess stresses are P_e = 4,665 psi and Q_e = 3,165 psi.

The elastic modulus was not available for the individual measurements but the range of the elastic modulus for the limestone was 8.0 to 9.7 million psi. The strains are calculated using an elastic modulus of 9 million psi. The strains from the maximum and minimum horizontal stresses are 611 and 444 micro strains.

4.2.3 Pittsburgh Coal Seam

The Pittsburgh coal seam is located in southwestern Pennsylvania, southeastern Ohio and northern West Virginia. There was information available on the horizontal stress from three different sites in three different mines. Site one was in the Bethlehem Steel Mine # 60 located about 10 miles east of Washington, PA (Agarwal and Mayer, 1979). Sites 2 and 3 were located about 3 miles apart and about 20 miles southwest of site one. The stresses were measured using the USBM borehole deformation gage and overcoring technique.

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The horizontal stresses at site one were calculated from a three-dimensional stress determination (Agarwal and Mayer, 1979). The three holes used to determine the stress field were drilled into the roof but none were vertical holes. Therefore, the horizontal stress determined from the three-dimensional analysis must be used for the site and not the stresses from the individual measurements. All the measurements at the site were made in a sandstone unit. Based on the tests conducted on rock from the site, the elastic modulus in the horizontal plane ranged from 1.5 to 2.0 million psi and averaged 1.8 million psi. This average elastic modulus and the calculated horizontal stresses from the three-dimensional stress determination were used to calculate the elastic strains for the site.

At sites 2 and 3, the stresses were determined in vertical holes drilled in the roof. Therefore, the individual stress measurements as well as the average horizontal stress at each site were used in the analysis.

For the Pittsburgh seam measurements, the site elastic modulus ranges from 1.8 to 7.65 million psi and the depth from 400 to 800 ft. The average site strain from the maximum horizontal stress varies from 403 to 736 micro strains and the strains from the minimum horizontal stress from 285 to 569 micro strains.

4.2.4 Lower Kittanning Seam

The lower Kittanning Seam is mined in northern West Virginia and central and southwestern Pennsylvania. Stress data was available from 2 mines, the Tanoma Mine near Indiana, Pennsylvania and a mine near Philippi, West Virginia. The mines are approximately 100 miles apart. Both mines have experienced sufficiently severe ground control problems related to the horizontal stress that the mines have either experimented with or used stress relief mining techniques (Dolinar et al., 2000; Aggson and Mouyard, 1988A, 1988B). The USBM borehole deformation gage and overcoring technique was used to determine the stresses at both mines.

The average site strains from the maximum horizontal stress are 575 and 703 micro strains and the strains from the minimum horizontal stress are 481 and 528 micro strains. In general, the levels of strain appear to be about 20 pct higher in the mine in West

Virginia. The site elastic modulus and depths are for the Tanoma site 4.29 million psi and 720 ft and for the Philippi site 5.8 million psi and 720 ft.

4.2.5 Summary of Northern Appalachian Region

This region includes stress measurements made in the coal and limestone mines of southwestern Pennsylvania, northern West Virginia and eastern Ohio. The data indicates that there is a substantial range of the maximum horizontal stress magnitude as well as a large range in the site depths. The maximum site stresses range from 1,324 to 6,910 psi. Over the region the site depth varies from 400 to 2,300 feet and the site elastic modulus from 1.8 to 11.2 million psi. The strains from the maximum horizontal stress for this region range from 403 to 736 micro strains and the strain from the minimum horizontal stress from 285 to 569 micro strains.

4.3 EASTERN MID-CONTINENT REGION

This region encompasses sites west of the Appalachian Mountains located in the Illinois basin, Alabama, Tennessee and northern Kentucky. In the Illinois basin, stress measurements from 8 sites in six mines were examined with the measurements being made in both the Springfield # 5 and the Herrin # 6 seams. These measurements were made using the USBM borehole deformation gage and overcoring technique. Some mines within the Illinois basin have experienced ground control problems related to the horizontal stress (Blevins, 1982; Blevins and Dopp, 1985; Hanna et al, 1986; Miller 1998). Core disking, another indication of a substantial horizontal stress in comparison to the rock strength has also been observed at some locations (Hanna et al., 1986). There is one site in a limestone mine in northern Kentucky, two sites from the Pratt coal seam in Alabama and one site from a zinc mine in the dolomite formations of eastern Tennessee. The measurements from these mines were also obtained using the USBM borehole gage and overcoring technique. The CSIRO HI-cell was used to determine the horizontal stresses at a site in the Blue Creek/Mary Lee seams in Alabama.

A summary of the individual stress measurement data from each site including the maximum and minimum horizontal stresses, excess horizontal stresses, elastic modulus

and calculated strains are given in Appendix D, table D-1. Table 4-4 gives a summary of the horizontal stresses for each site.

Table 4-4. Summary of horizontal stresses by site in the eastern Mid-Continent region.

Mine	Horizontal stress			Excess stress, psi		Elastic modulus, 10^6 psi	Depth, ft
	Maximum, psi	Minimum, psi	Direction of maximum	Maximum	Minimum		
Wabash, site 1	1245	963	East-West	889	607	3.11	970
Wabash, site 2	1429	823	N 80 °E	1117	511	2.9	850
Wabash, site 3	1459	589	N 75 °W	1144	274	2.85	860
Monterey	888	573	N 64 °E	782	467	1.67	290
Galatia	1767	531	N 73 °E	1558	322	2.96	570
Peabody #2	969	896	N 81 °E	859	786	2.2	300
Peabody #10	1800	750	N 69 °E	1668	618	2.84	360
Turris	1986	1010	N 49 °E	1885	909	8.57	275
Campbell County, KY	3784	1320	N 78 °E	3516	1052	9.32	730
Immel Mine, TN	3294	1281	N 61 °E	2954	942	7.96	925
North River Mine, site 1, AL	2123	297	N 57 °E	1940	114	5.42	500
North River Mine, site 2, AL	1042	385	N 69 °E	870	213	4.72	470
Jim Walters #7, AL	3050	1520	N 71 °E	2364	834	5.4	1870

4.3.1 Wabash Mine

The mine is in the Springfield # 5 seam located near Keansburg, Illinois. There were three measurement sites within the mine (Ingram and Molinda, 1988). For the more general analysis and for calculation of the elastic strains for each site, all measurements are used from hole 1, only the deepest three measurements from hole 2 and only the four deepest measurements from hole 3. This resulted in measurements that were 9.9 ft or deeper into the roof being used in the analysis. The deeper measurements reduced the potential influence of the opening on the results. The average strains from the maximum horizontal stress are for hole 1, 400 micro strains, for hole 2, 493 micro strains, and for

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hole 3, 512 micro strains. From the minimum horizontal stress, the average strains are for hole one, 310 micro strains, for hole two, 284 micro strains and for hole three, 207 micro strains. The range of the individual elastic modulus from 2.63 to 3.39 million psi and the variation of the site depths from 860 to 950 ft are both limited. Hole 1 was about 1,500 ft from a large normal fault with the site possibly influenced to some degree by that feature.

4.3.2 Monterey Mine

The mine is located near Carlinville, Illinois in the Herrin # 6 seam. Because, the two shallower measurements at 4.33 and 6.33 ft show less strain from the maximum horizontal stress than the other measurements, these measurements may be under the influence of the opening. Therefore, only the two deeper measurements are used in the analysis. Based on the deepest two measurements, the average strain due to the maximum horizontal stress is 532 micro strains while the average strain from the minimum horizontal stress is 343 micro strains. The range of the individual elastic modulus is from 1.44 to 1.9 million psi while the site depth is 290 ft (Beerkircher, 1994).

4.3.3 Galatia Mine

The mine is located near Galatia, Illinois in the Springfield # 5 seam. Although measurements were obtained at three sites in the mine, elastic properties were available from only one hole (Ingram and Molinda, 1988). Only the three deepest measurements from 10.1 to 13.1 ft are used in the analysis. The average strain from the maximum horizontal stress is 579 micro strains while the strain from the minimum horizontal stress is 179 micro strains. The range of the elastic modulus for the last three measurements is only from 2.81 to 3.17 million psi. The site depth is 570 ft.

4.3.4 Turris Mine

The mine is located near Elkhart, Illinois in the Springfield #5 seam. The measurements are at a relatively shallow depth in the roof at 5.8 and 6.2 ft and may be under the influence of the opening. The range in the elastic modulus is only from 8.08 to 9.05 million psi. The average strain from the maximum horizontal stress is 232 micro

strains while the average strain from the minimum horizontal stress is 118 micro strains. The site is at a depth of 275 ft and is near a bedrock valley.

4.3.5 Peabody # 10 Mine

The mine is located near Pawnee, Illinois in the Herrin # 6 seam. The depth of the site is 360 ft. For the general analysis only the last three measurements obtained at depths from 9 to 11 feet from the opening are used (Hanna et al., 1991). For these last three measurements there is a large range in the elastic modulus from 1.28 to 5.7 million psi. The average strain from the maximum horizontal stress based on these last three measurements is 634 micro strains while the average strain from the minimum horizontal stress is 264 micro strains.

4.3.6 Peabody #2 Mine

The mine is located near Henderson, Kentucky in the Springfield # 5 seam. Only the deeper three measurements are used in the more general analysis (Wright et al., 1980; Unrug et al., 1984). At this site, for the last three measurements only one elastic modulus was obtained, an elastic modulus of 2.2 million psi, therefore the stresses and strains are averaged from the last three measurements. Based on these last three measurements, the strain from the maximum horizontal stress is 440 micro strains while the strain from the minimum horizontal stress is 407 micro strains. The depth of the site is 300 ft.

4.3.7 Ft. Campbell Limestone

The mine is located in the Ft. Campbell Limestone in Campbell County, KY at a depth of 730 ft. A complete three-dimensional stress determination was made using the USBM borehole deformation gage and overcoring technique.

The horizontal stresses were calculated from the three-dimensional stress determination. The elastic modulus for the measurements used in the calculations ranged from 8.1 to 11.0 million psi where the average elastic modulus was 9.32 million psi. The resulting average strains from the maximum and minimum horizontal stresses are 406 and 142 micro strains.

4.3.8 North River Mine

This mine is located near Tuscaloosa, Alabama in the Pratt seam with stress measurements made at two sites. The depth of site one was 500 feet. At site one, there were 5 measurements made at depths ranging from 7 to 11 ft in the mine roof, however, the elastic modulus was determined for only 4 of the measurements. The elastic modulus ranges from 5.11 to 5.91 million psi. At site one, the strains from the maximum and minimum site stresses are 392 and 55 micro strains.

Site 2 was at a depth of 470 ft and about 2.3 miles from site one. The site was 600 ft from a large normal fault. Only the deepest 3 measurements from 8 to 10 ft are used in the analysis. The elastic modulus ranges from 4.45 to 5.12 million psi. The average site strains from the maximum and minimum stress are 221 and 87 micro strains.

4.3.9 Jim Walters # 7 Mine

The mine is located near Brookwood, Alabama in the Blue Creek/Mary Lee seams. The stresses were determined using the CSIRO HI-Cell and overcoring technique (Brasfield and Hendon, 1994; Hendon et al., 1995). The site depth was 1,870 ft. The specific elastic modulus used in the calculations is not given but the average elastic modulus of the main roof where the measurements appear to have been obtained is reported. The elastic modulus based on physical properties determined on vertically oriented core is 5.4 million psi with a standard deviation 1.1 million psi. Using this elastic modulus, the average site strain from the maximum horizontal stress is 565 micro strains and from the minimum horizontal stress 281 micro strains.

4.3.10 Immel Mine

The mine is located about 10 miles east of Knoxville, Tennessee in the dolomite and limestone formations that contain zinc mineralization (Crawford and Hoagland, 1968). The depth of the site was 925 ft. Measurements were made in a vertical down hole, hole 3 and a vertical up hole, hole 4. The elastic modulus varied from 4.86 to 11.94 million psi while the average site elastic modulus was 7.96 million psi. Much of the variation in the elastic modulus may be due to mineralization. The average site

strains are from the maximum horizontal stress, 414 micro strains and from the minimum horizontal stress, 161 micro strains.

4.3.11 Summary of Eastern Mid-Continent Region

The region includes sites in Illinois and western Kentucky in both the Springfield #5 and Herrin # 6 seams of the Illinois basin, a site in limestone in northern Kentucky, two sites in the Pratt seam and one site in the Blue Creek/Mary Lee seams in Alabama and a site in dolomite formations in eastern Tennessee. Over this region the site elastic modulus varies from 1.67 to 9.32 million psi and the depth ranges from 275 to 1,870 ft. The average site strains from the maximum horizontal stress range from 221 to 634 micro strains while the average site strains from the minimum horizontal stress ranges from 55 to 407 micro strains. In general, most sites in this region have very biaxial horizontal stresses and strains.

CHAPTER 5: BECKLEY COAL SEAM

Information regarding the depth of the sites and the elastic modulus for the individual stress measurements was available from 15 sites within the Beckley coal seam. Therefore, this geographically concentrated set of data is analyzed with respect to the elastic modulus and the depth. In this part of the analysis, the site data from the Beckley #4 mine in the Sewell seam is not included. The developed regression models are based on the data found in Appendix A, tables A1 and A2.

In the analysis throughout most of this section, the individual measurements are used rather than site averages. This is done to evaluate more completely the variation that may occur between the stress and the elastic modulus since the elastic modulus will change between each measurement. However, local variation between measurements may occur beyond that caused by the elastic modulus, therefore to eliminate the local variation in one section an analysis is done using the average site stresses and elastic properties. Further, several measurements from a site are usually combined to produce an average site stress that is then used in mine design evaluation.

5.1 VARIATION OF THE HORIZONTAL STRESS WITH THE ELASTIC MODULUS

To evaluate the variation of the horizontal stress with respect to the elastic modulus, a regression line is fit through all 60 individual stress measurements from the Beckley seam. Figure 5-1 shows a graph of the maximum horizontal stress versus the elastic modulus along with the resulting regression line. The regression equation is

$$P = 180\,E + 2666. \tag{5.1}$$

The coefficient of determination is only 0.12. There is little correlation between the elastic modulus and the maximum horizontal stress. This indicates that the strain field is not very uniform across the Beckley coal seam.
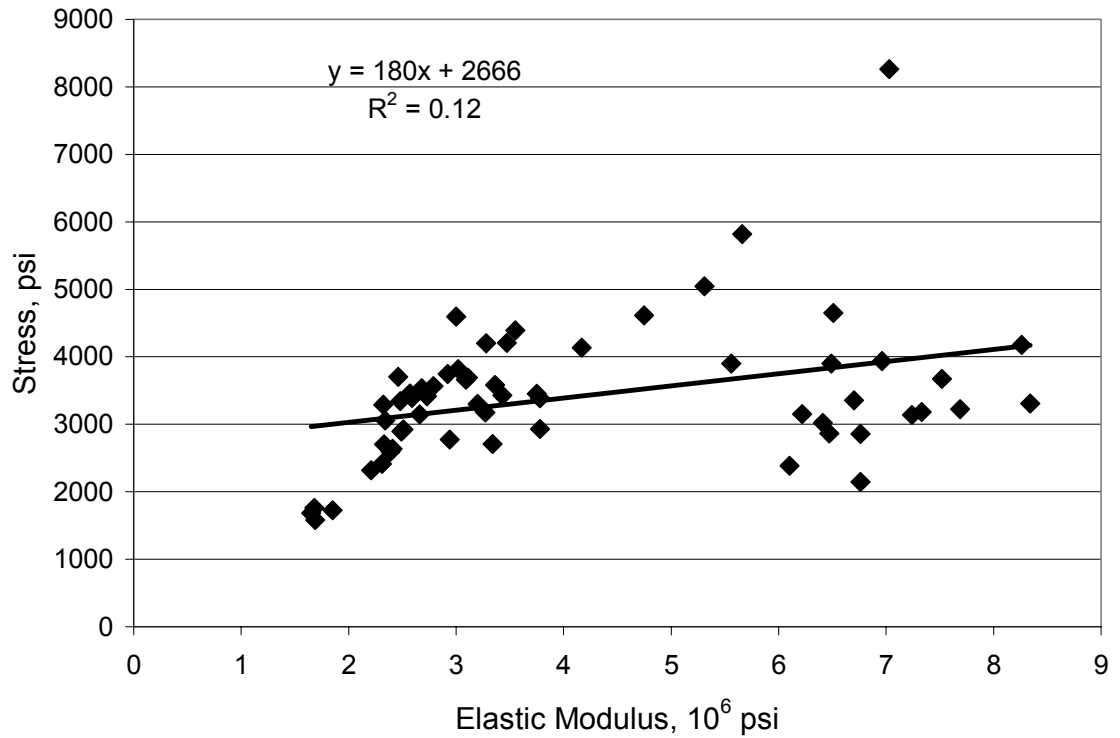
Figure 5-1. The maximum horizontal stress versus the elastic modulus, Beckley coal seam (combined strain zones).

Table 5-1 shows the average strain resulting from the maximum and minimum horizontal stress for each hole. The average strain is calculated based on the strains determined from the individual stress measurements at each site. Essentially, in the Beckley seam/coalfield there are two different strain conditions, a high strain and a low strain field. The high strain field has average site strains above 885 micro strains while the low strain field has average site strains below 602 micro strains. Further, the two strain conditions are geographically distinct. The low strain area includes the sites from the Beckley #1 Mine and the adjacent southwest section of the Maple Meadows Mine (Figure 5-2). The high strain area includes the sites from the northeast section of the Maple Meadows Mine and the adjoining Beckley and Bonny Mines as well as the Beckley #2 Mine.

Because of the two distinct strain fields, each strain field is analyzed separately to determine if the horizontal stress varies with the elastic modulus. Figure 5-3 shows a graph of the maximum horizontal stress versus the elastic modulus from the individual

stress measurements for the high strain area. A regression line is fit through the data with the resulting equation of

$$P = 878 E + 703. \tag{5.2}$$

Table 5-1. Average horizontal strains from the maximum and minimum horizontal stresses by site in the Beckley coal seam[1].

Mine	Hole	Average maximum micro strain	Standard deviation	Pct of strain	Average minimum micro strain	Standard deviation	Pct of strain	Elastic modulus 10^6 psi	Standard deviation	Depth, ft
Low Strain										
Beckley 1	2	469	36	7.7	279	25	9.0	6.77	0.55	1130
Maple Meadows	6	432	41	9.5	420	53	12.6	6.32	0.2	708
Maple Meadows	8	601	104	17.3	333	41	12.3	7.09	1.02	1025
Maple Meadows	10	481	66	13.7	239	30	12.6	6.92	0.24	807
Beckley 1	15	437	86	19.7	242	54	22.3	7.32	0.5	700
Average		484	69	14.3	303	78	25.7	6.88		874
High Strain										
Beckley #2	3	1021	2	0.2	742	12	1.6	2.26	0.07	1100
Bonny	4	886	192	21.7	846	185	21.9	3.59	0.24	1136
Bonny	5	1018	114	11.2	554	137	24.7	6	0.96	1148
Maple Meadows	7	1008	423	42.0	730	344	47.1	4.44	1.31	735
Maple Meadows	9	1296	147	11.3	957	201	21.0	2.46	0.08	814
Beckley Mining	11	1049	215	20.5	850	282	33.2	2.95	0.58	640
Beckley Mining	12	1260	53	4.2	987	32	3.2	2.94	0.29	870
Beckley Mining	13	1157	128	11.1	863	134	15.5	2.7	0.24	800
Beckley Mining	14	1076	104	9.7	651	82	12.6	3.5	0.41	1040
Beckley #2	16	1047	61	5.8	783	10	1.3	1.72	0.09	350
Average		1082	123	11.4	796	133	16.7	3.26	1.23	863

[1]Each hole is a separate site location. The individual measurements used to develop the average values are given in Appendix A.
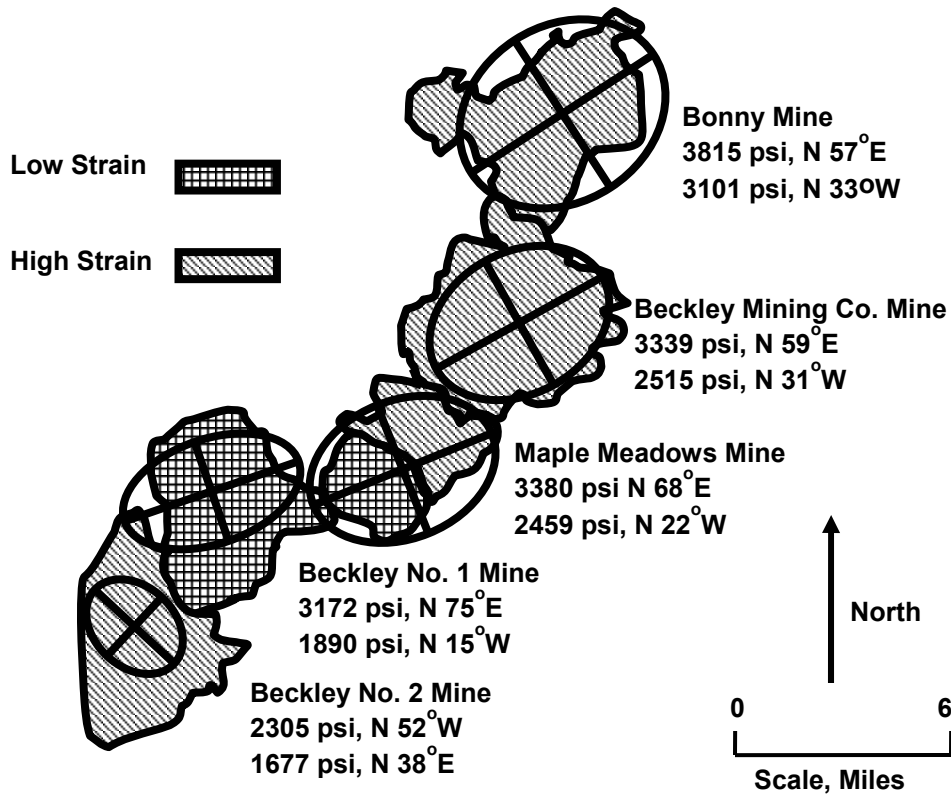
Figure 5-2. Low and high strain zones in the Beckley Seam (modified from Agapito et al., 1980A).
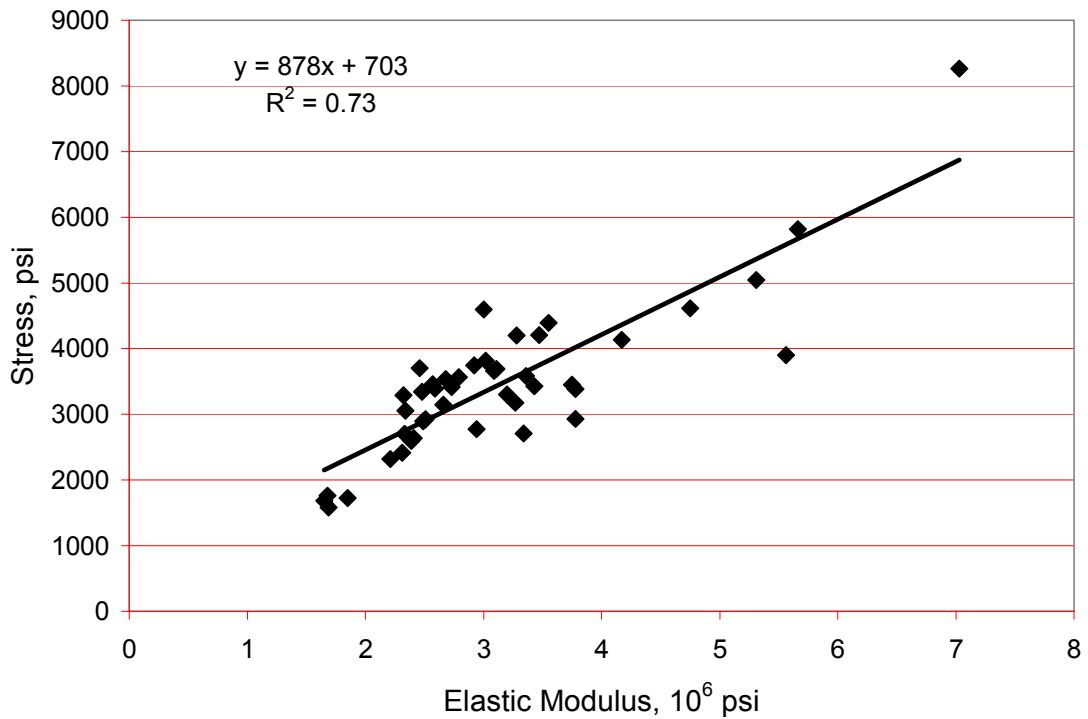
Figure 5-3. The maximum horizontal stress versus the elastic modulus, Beckley coal seam (high strain zone).

The coefficient of determination is 0.73. There is a fairly strong correlation between the maximum horizontal stress and the elastic modulus. However, there is still sufficient variation in the strain field to result in a coefficient of determination that is somewhat less than one. Some of this variation is the result of the strains varying horizontally across the zone as seen by the difference in average between holes (table 5-1). However, some of the variation is also the result of the strain field varying vertically or between measurements in the same hole as can be seen by the standard deviation for each hole in table 5-1. Further, any difference in the strain field resulting from the variation in depth between sites has not been taken into account.

Figure 5-4 shows a graph of the maximum horizontal stress versus the elastic modulus for the low strain region. Again, a linear regression is fit through the data with the resulting equation of

$$P = 267\,E + 1439. \qquad\qquad (5.3)$$
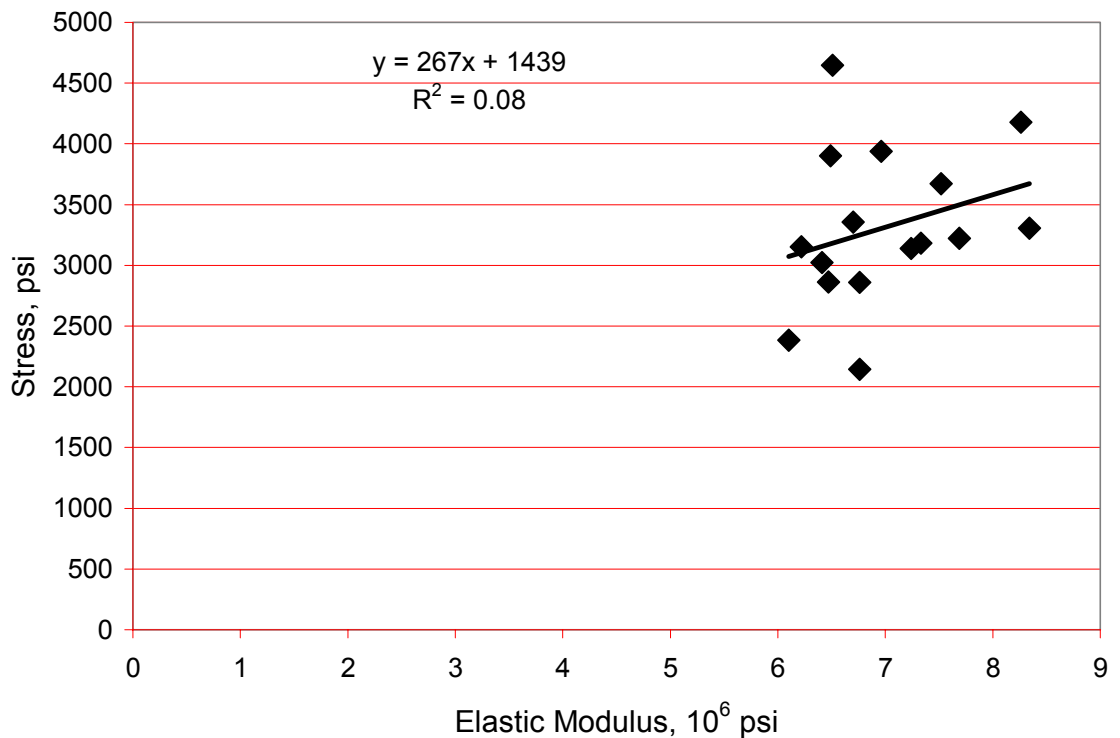
Figure 5-4. The maximum horizontal stress versus the elastic modulus, Beckley coal seam (low strain zone).

The coefficient of determination is only 0.08. Although the trend is for increasing horizontal stress with the elastic modulus, the correlation is very poor even though it appears the measurements are taken from essentially the same strain field. Further, the increase in stress with the elastic modulus is much less than for the high strain field as indicated by the coefficients for the elastic modulus for each equation. With the lower strain field, the affects on the increase in the horizontal stress are proportionally less than for a higher strain field and in this case, the changes are not sufficient to overcome the local or mine wide variations in the strain field. Further, the range of the elastic modulus is limited with this set of measurements, ranging only from 6.1 to 8.34 million psi. This limited range results in a less reliable model.
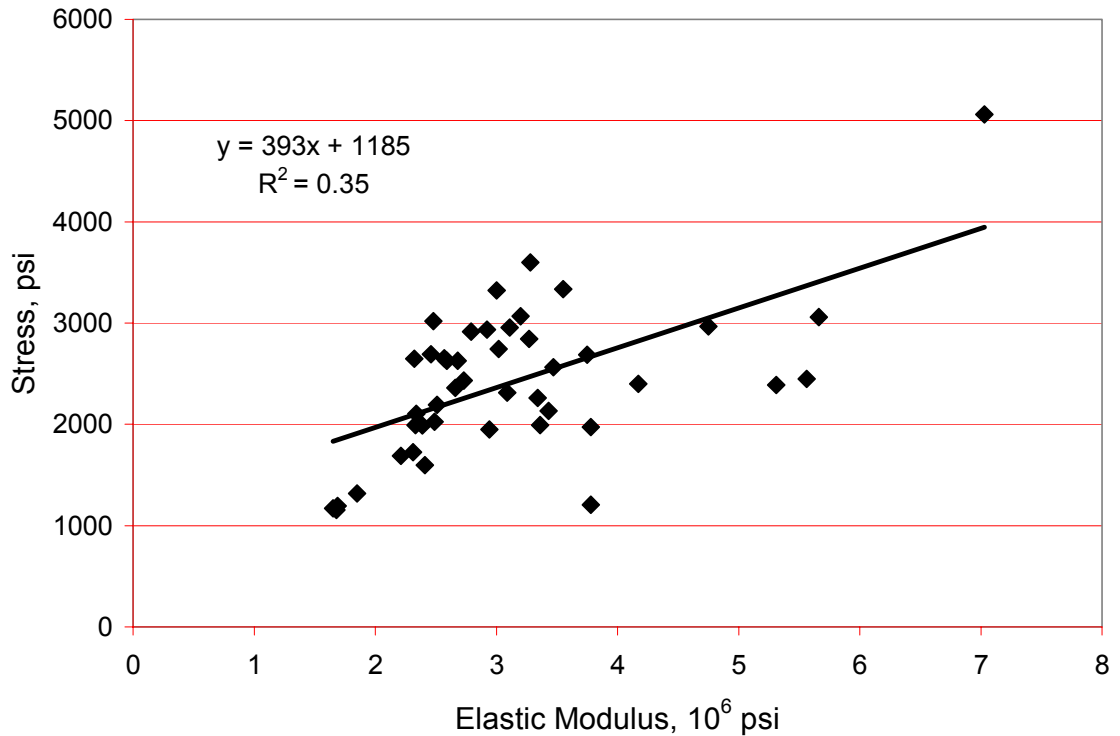
Figure 5-5. The minimum horizontal stress versus the elastic modulus, Beckley coal seam (high strain zone).

The relationship between the minimum horizontal stress and the elastic modulus is also examined. Again, the minimum horizontal stress is segmented into two distinct

strain fields. Figure 5-5 shows the minimum horizontal stress versus the elastic modulus for the high strain zone. The resulting regression equation is

$$Q = 393\ E + 1185. \tag{5.4}$$

The coefficient of determination is 0.35. Although there is trend of increasing horizontal stress with the elastic modulus, the correlation is much less than for the maximum horizontal stress. The larger constant, the relatively higher standard deviation of the strain and the greater site strain range indicates that the strain field from the minimum horizontal stress across the Beckley seam is not as uniform as the strain from the maximum horizontal stress. Further, the lowest strain site has the highest elastic modulus (table 5-1).

Figure 5-6 shows the minimum horizontal stress versus the elastic modulus for the low strain zone. Again a regression line is fit through the data. The coefficient of determination is only 0.03. Essentially, there is no correlation between the minimum horizontal stress and the elastic modulus for the low strain zone.
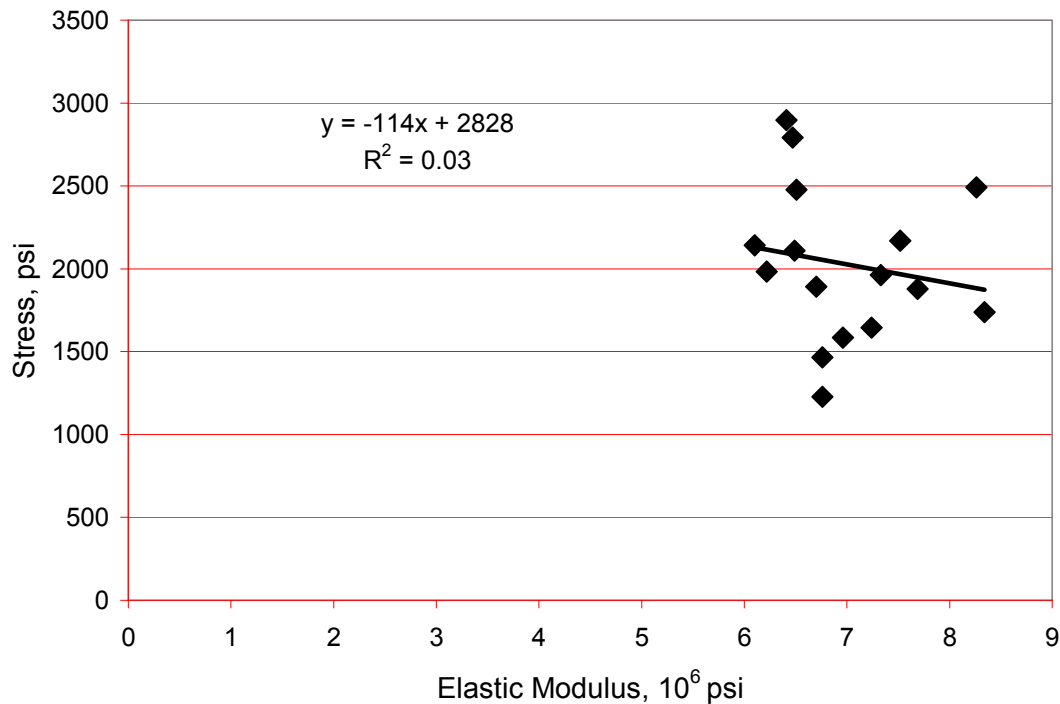
Figure 5-6. The minimum horizontal stress versus the elastic modulus, Beckley coal seam (low strain zone).

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There is only a very weak relationship between the minimum horizontal stress and the elastic modulus. This in part is due to the strain fields from the minimum horizontal stress being less uniform. This can be seen with the standard deviation of the minimum strain being a much higher percent of the average than for the maximum strain (table 5-1). Further, these strains are much lower than the maximum strains and, therefore, there will be less increase in stress with the elastic modulus. There does appear to be a difference between the two stress components with the minimum component not being as strongly influenced by the elastic modulus.

5.2 VARIATION OF HORIZONTAL STRESS WITH DEPTH

Since there is a range of depths for the sites in the Beckley seam, the influence of depth on the measurements is evaluated. When examining the Beckley data for depth effects, all the data is combined where the data is not separated based on the two distinct strain fields. Further, only the site average maximum horizontal stress is used in the analysis. The average is used to give equal weight to all sites. Figure 5-7 shows a graph of the average maximum horizontal stress from each site versus the depth with a regression line fit through the data. The resulting equation is

$$P = 2.08\,D + 1629. \tag{5.5}$$

However, the coefficient of determination is only 0.22. The correlation is low but there is a general trend of increasing maximum horizontal stress with depth. In fact, the horizontal stress is increasing at a rate of 2.1 psi/ft. This is twice the rate for the expected increase of the vertical stress. However, when the depth coefficient is compared to zero, the t statistic of 1.94 indicates that the coefficient is not significantly greater than zero at a 0.05 significance level.

Further, one data point controls to a large extent the increase of the maximum horizontal stress with depth, the Bonny Mine, hole 5, with a maximum horizontal stress of 6,109 psi at a depth of 1,148 ft. Without this data point, the depth factor drops to 1.1 psi/ft of depth while the coefficient of determination is only 0.12. However, it may not be the depth that is causing such a high horizontal stress at this site but the relatively

high elastic modulus of 6 million psi in the high strain zone. Therefore, no apparent significant increase in the maximum horizontal stress with depth over the Beckley seam is observed. However, the topography in the Beckley area is mountainous and therefore variable and complex.
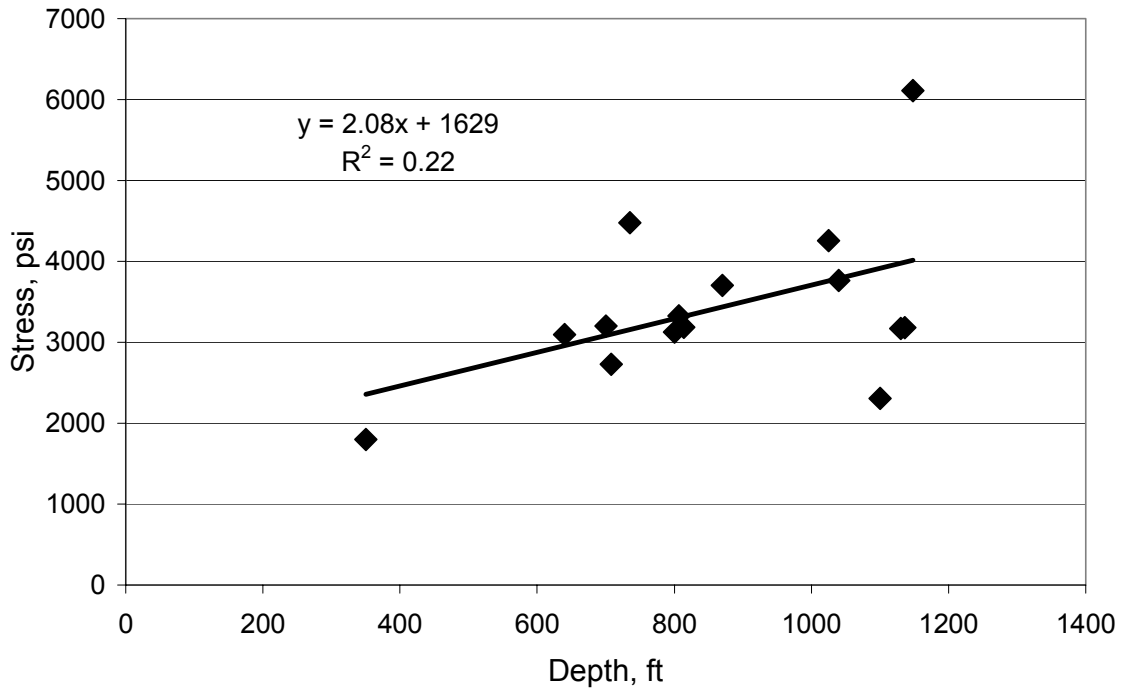
Figure 5-7. The maximum horizontal stress versus the depth, Beckley coal seam.

Figure 5-8 shows the strain from the maximum horizontal stress versus the depth. These strains can be considered as the stress normalized by the elastic modulus. The strain actually decreases slightly with depth though the coefficient of determination of only 0.001 indicates that there is no relationship between the depth and the strain. Essentially, when the effects of the elastic modulus are removed from the stress data, there is no depth factor. Further, the difference in the two strain fields (low and high) is not the result of depth otherwise there should be a strong relationship between depth and the strain.
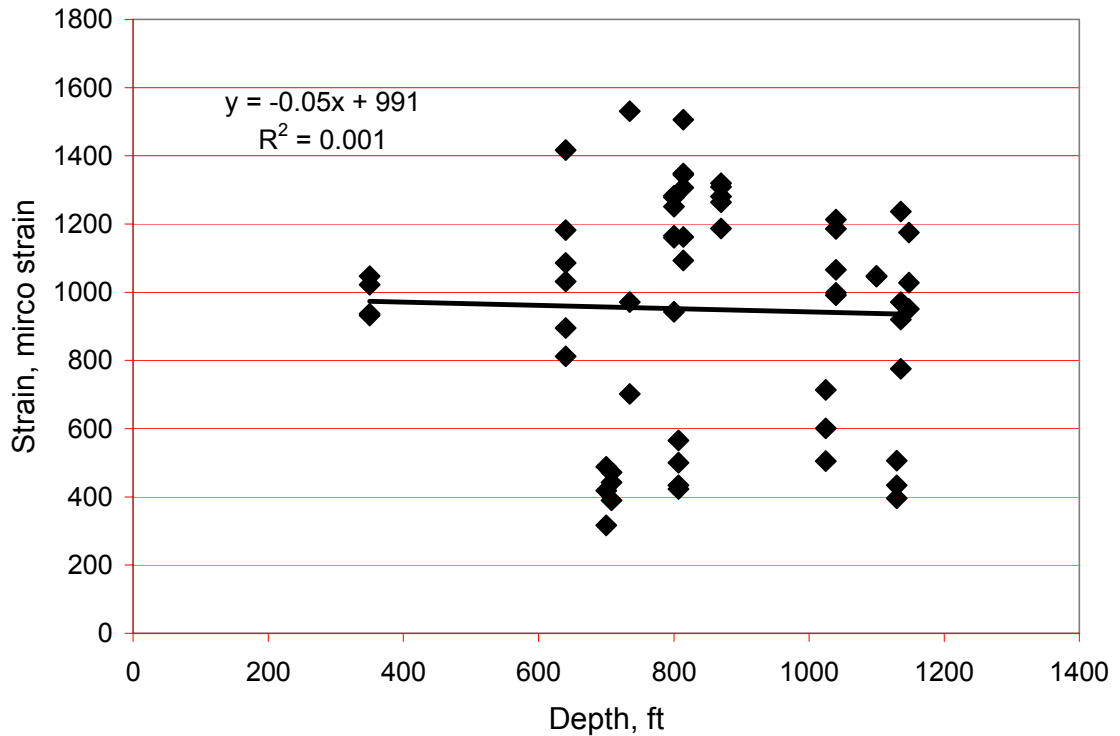
Figure 5-8. The strain from the maximum horizontal stress versus the depth, Beckley coal seam (combined strain zones).

5.3 VARIATION OF HORIZONTAL STRESS WITH BOTH THE ELASTIC MODULUS AND DEPTH

A multiple regression analysis with the horizontal stress as the dependent variable and the elastic modulus and depth as the independent variables is also conducted. In this case, the individual stress measurements are used. However, with the inclusion of the elastic modulus, the analysis must be separated into the low and high strain zones. From a regression analysis on the data from the low strain zone, the following equation results

$$P = 1.53\ D + 169\ E + 797. \tag{5.6}$$

The multiple correlation coefficient squared is 0.24. This is certainly an improvement over the coefficient of determination for just the elastic modulus. The maximum horizontal stress is increasing at 1.5 psi/ft but the t statistic of 1.67 indicates that the coefficient is not significantly greater than zero at a 0.05 significance level. The strain coefficient is low at 169 micro strains.

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For the high strain zone, the multiple regression analysis results in the following equation

$$P = 0.73\,D + 797\,E + 343. \tag{5.7}$$

The multiple correlation coefficient is 0.75. There is little improvement over the regression analysis with only the elastic modulus. Further, the t statistic for the depth coefficient is only 1.55 where the coefficient is not significantly greater than zero at a 0.05 significance level.

The multiple linear regression analysis provides little or no additional information to explain the variation of the maximum horizontal stress in the high strain zone. This is to a large measure due to the weak influence of the depth on the maximum horizontal stress. For the low strain zone, although the inclusion of depth has improved the model, the depth factor is not significantly greater than zero. Therefore, the depth does not appear to be a major factor in the change in magnitude of the maximum horizontal stress in the Beckley seam.

5.4 EXCESS HORIZONTAL STRESS

To establish the relationship between the elastic modulus and excess horizontal stress, a linear regression is fit through both the high and low strain data sets. For the maximum excess horizontal stress from the high strain zone, the resulting equation is

$$P_e = 824\,E + 578. \tag{5.8}$$

The coefficient of determination is 0.72. There is fairly good correlation between the elastic modulus and the maximum excess horizontal stress where the model can explain about 72 percent of the variation in the maximum excess horizontal stress. Fitting the linear regression through zero results in the relationship between the elastic modulus and the maximum excess horizontal stress without a constant. The resulting equation is

$$P_e = 988\,E. \tag{5.9}$$

The coefficient of determination is 0.69. The model fit is only slightly reduced by constraining the fit through zero. From the coefficient of the equation, the excess or tectonic strain component producing the maximum excess stress is 988 micro strains.

The equation for the minimum excess horizontal stress for the high strain zone is

$$Q_e = 339 \, E + 1061. \tag{5.10}$$

The coefficient of determination is 0.30. The correlation is poor and the model can only explain 30 percent of the variation of the minimum excess horizontal stress. Fitting the regression line through zero results in a negative coefficient of determination. The variation of the minimum excess horizontal stress is much less dependent on the elastic modulus than the maximum excess horizontal stress.

For the low strain region, the coefficient of determination from fitting a regression through the data is for the maximum excess horizontal stress only 0.07 and for the minimum excess horizontal stress only 0.04. Essentially, for the low strain zone, there is little or no relationship between the excess horizontal stress and the elastic modulus. Regression line fits are so poor that the model coefficients are meaningless.

5.5 VARIATION OF THE HORIZONTAL STRESS WITH THE ELASTIC MODULUS BASED ON SITE AVERAGE STRESSES

The relationship between the horizontal stress and the elastic modulus is evaluated using the site average stresses and not the individual stress measurements. This should reduce the effects of local variations in the stress and strain fields. Further, individual measurements are normally combined to develop the average stress field at a site. Table 5-2 shows the regression equations for the maximum horizontal stress versus the elastic modulus based on both the individual measurements and the site averages.

Table 5-2. Comparison of the regression parameters and statistics based on individual or average site stresses, Beckley coal seam.

Analysis	Stress component	Elastic modulus coefficient, K_1, micro strain	Constant, K_2	Coefficient of determination, R^2
Measured stress-high strain zone				
Individual	Maximum	878	703	0.73
Average	Maximum	926	459	0.92
Individual	Minimum	393	1185	0.35
Average	Minimum	437	1077	0.69
Measured stress-low strain zone				
Individual	Maximum	268	1439	0.08
Average	Maximum	867	-2637	0.33
Individual	Minimum	-114	2828	0.03
Average	Minimum	-702	6897	0.38

For the high strain zone, the regression coefficients and constants are similar. However, the correlations are much better when the site averages are used. For the maximum stress, the coefficient of determination went from 0.73 to 0.92 while for the minimum stress the coefficient of determination went from 0.35 to 0.69. This difference reflects the local variations in the strain field between individual measurements at a site.

For the low strain zone, the coefficient of determination certainly improves when the averages are used. However, the regression coefficients and constants for the equations are quite different. This reflects the narrowing of an already small range of the elastic modulus. For the individual stress measurements, the elastic modulus ranges from 6.1 to 8.34 million psi while for the site averages, the elastic modulus ranges from only 6.32 to 7.32 million psi.

5.6 VARIATION OF THE HORIZONTAL STRESS WITH THE ELASTIC MODULUS AT INDIVIDUAL SITES AND MINES

By looking at the individual sites and mines, there should be less variation in the strain field and potentially better correlation between the horizontal stress magnitude and the elastic modulus. Therefore, the relationship between the elastic modulus and the horizontal stress for individual sites and mines is evaluated.

Equation 3.1 is used as the regression model to fit to the maximum horizontal stress and elastic property data for each of the individual sites. Table 5-3 shows the resulting coefficients, constants and the coefficients of determination from the equations for each site.

Table 5-3. Constants and correlations from a regression fit for the maximum horizontal stress from individual sites in Beckley coal seam.

Site/hole	Number of measurements	Coefficient K_1	Constant K_2	Coefficient of determination R^2	Elastic modulus range, 10^6 psi	Elastic modulus span, 10^6 psi
Low Strain						
Beckley#1, hole 2	3	52	2868	0.40	6.22-8.34	2.12
Maple Meadows, hole 6	3	1262	-5357	0.97	6.1-6.47	0.37
Maple Meadows, hole 8	3	-55	4559	0.02	6.47-8.26	1.79
Maple Meadows, hole 10	4	328	976	0.02	6.76-7.24	0.48
Beckley #1, hole 15	3	1386	-7148	0.78	6.76-7.69	0.93
High Strain						
Beckley #2, hole 3	2	-1050	4888	1.00	2.21-231	0.1
Bonny, hole 4	4	-220	4243	0.01	3.27-3.78	0.51
Bonny, hole 5	3	1706	-4045	1.00	5.31-7.03	1.72
Maple Meadows, hole 7	3	-206	5132	0.52	3-5.56	2.56
Maple Meadows, hole 9	6	1976	-1735	0.19	2.34-2.57	0.23
Beckley Mining, hole 11	6	224	2338	0.15	2.32-3.78	1.46
Beckley Mining, hole 12	5	878	1045	0.83	2.59-3.28	0.69
Beckley Mining, hole 13	6	122	2582	0.01	2.33-2.94	0.61
Beckley Mining, hole 14	5	446	2188	0.31	3.09-4.17	1.08
Beckley # 2, hole 16	4	211	1453	0.06	1.65-1.85	0.2

There is a wide range of coefficients of determination with several sites showing poor or little or no correlation. The poor correlations result to a large degree from the very narrow range of the elastic modulus measured at each site. The span for the elastic modulus ranged from 0.1 to 2.56 million psi. In general, the regression analysis with the wider ranges of the elastic modulus gives a better correlation. Therefore, a sufficient range of the elastic modulus is usually required to overcome the local variations in the strain field and to establish a reliable model. However, there are some exceptions where a narrow range has resulted in a higher correlation. There is also at least one site with a

wider range of elastic modulus yet with almost no correlation. This reflects the significant variation of the strain field between measurements.

There is also a wide range of coefficients and constants that were determined even in essentially the same strain field with some of the coefficients being negative. Again this reflects the narrow range of the elastic properties used in the regression analysis. With such a narrow range of the elastic modulus, the values of the coefficients and constants can vary significantly.

To develop a broader range of the elastic modulus, the data from each mine is considered. Table 5-4 shows the coefficients, constants and the coefficients of determination from a regression analysis for each mine. However, the Maple Meadows Mine sites are separated into high and low strain groups for the analysis.

Table 5-4. Constants and correlations from a regression fit for the maximum horizontal stresses from each mine in the Beckley coal seam.

Mine	Number of measurements	Coefficient K_1	Constant K_2	Coefficient of determination R^2	Elastic modulus, 10^6 psi	
					Range	Span
Beckley #1	6	309	845	0.2	6.22-8.34	2.12
Beckley # 2	6	968	161	0.93	1.65-2.31	0.66
Beckley	22	545	1780	0.31	2.51-4.17	1.66
Bonny	7	1267	-1132	0.9	3.27-7.03	3.7
Maple Meadows (Low)	10	502	18	0.18	6.1-8.26	2.66
Maple Meadows (High)	9	354	2474	0.36	2.34-5.56	3.22

At the Bonny Mine, the span of the elastic modulus is sufficient to result in a very good correlation between the maximum horizontal stress and the elastic modulus. Figure 5-9 shows the maximum horizontal stress versus the elastic modulus for the mine. At the Bonny Mine, the strain field is sufficiently uniform with a large enough range of the elastic modulus for an adequate model to be developed. Further, fitting a regression line through the maximum excess horizontal stress data and zero results in the following equation

$$P_e = 933 \ E. \qquad\qquad (5.11)$$

The resulting coefficient of determination is 0.85. The mine is being subjected to a strain from the maximum excess horizontal stress of 933 micro strains.
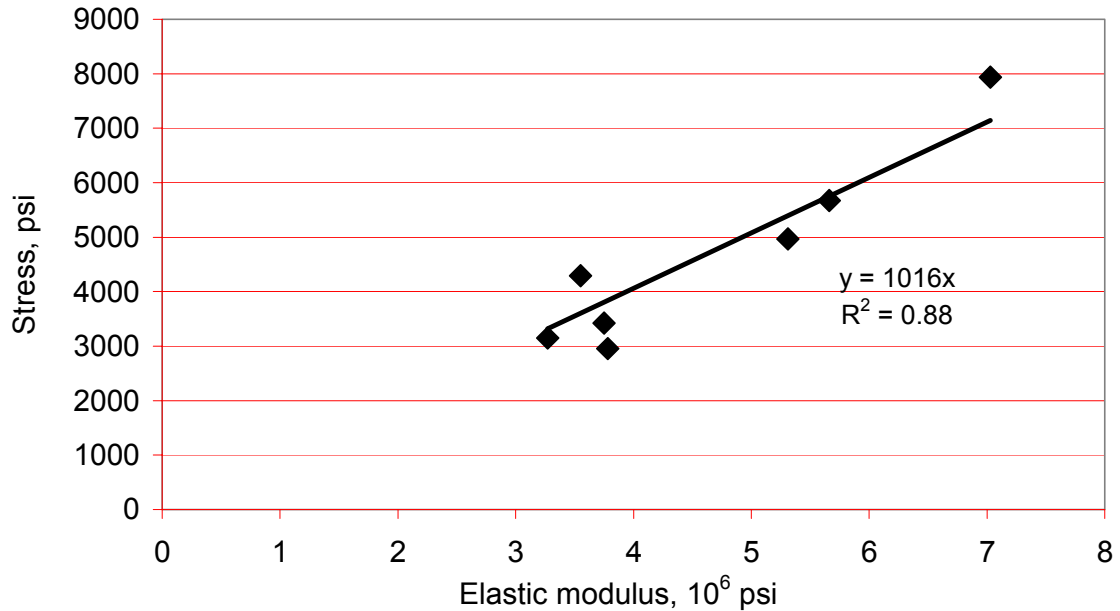
Figure 5-9. The maximum horizontal stress versus the elastic modulus, Bonny mine.

5.7 BECKLEY SEAM ANALYSIS-CONCLUSIONS

A sufficiently uniform strain field is required to develop adequate regression models. When all the Beckley seam data was combined there was little correlation between the maximum horizontal stress and the elastic modulus because of the large range in site maximum horizontal strains.

The sites in the Beckley seam can be separated into high and low strain zones that are geographically distinct. The high strain group contains those sites with strains from the maximum horizontal stress above 885 micro strains and the low strain group contains sites with strains from the maximum horizontal stress below 602 micro strains.

The elastic modulus explains much of the variation of the maximum horizontal stress in the high strain zone. For the high strain zone models, the coefficient of determination is 0.73 when individual stress measurements are used and 0.92 when the site averages are used.

A sufficient range of the elastic modulus is required to establish adequate relationships between the maximum horizontal stress and the elastic modulus. For the low strain zone there was little correlation between the maximum horizontal stress and the elastic modulus in part because of the limited elastic modulus range.

The minimum horizontal stress variation is less dependent on the elastic modulus than the maximum horizontal stress variation. For the minimum horizontal stress in the high strain zone, the coefficient of determination is only 0.35 for the individual measurements.

Depth did not cause a significant increase in the maximum horizontal stress across the seam even though the depth factor is 2.1 psi/ft. Further, the maximum horizontal stress normalized by the elastic modulus actually decreases with depth though not significantly. Essentially, the variation of the maximum horizontal stress that might be attributed to the depth can be explained by the elastic modulus.

CHAPTER 6.0: VARIATION OF STRAINS IN THE EASTERN UNITED STATES

If general or more general models are to be developed between the horizontal stress and the elastic modulus, the distribution of strains across the eastern United States needs to be examined. Based on the previous Beckley seam analysis, geographic regions where the strain fields are sufficiently uniform must be identified. Essentially, strains can be used to delineate what zones any stress models can be applied across and whether regional groupings can be used in the evaluation of the variation of the horizontal stress magnitude. If geographic regions with sufficiently uniform strains are established, the variation in the magnitude of the horizontal stress should be to a large degree dependent on the elastic modulus.

The analysis of regional site variation is developed by evaluation of the average site strains. However, the local site variations to the strain field are also examined. Essentially, this establishes the reliability of the average site strains. Besides the elastic properties, the variation of the strain field both locally and regionally will directly affect the magnitude and the variation in the magnitude of the horizontal stress.

In this section, the actual applied horizontal strains are calculated and used to evaluate the strain variation both locally and regionally. There are two horizontal strain components, the maximum and minimum applied horizontal strains that produce a horizontal stress. Further, to determine the strains locally, the average strain based on each measurement from a site is calculated and to develop strains regionally, the average strain from each site is combined with the average strains from other sites within a region.

6.1 DETERMINATION OF THE APPLIED HORIZONTAL STRAINS

The relationship between the maximum horizontal stress and the applied maximum and minimum horizontal strain is given by the following equation (Amadi, 1996)

$$P = E \, (\varepsilon_{pA} + \nu\varepsilon_{qA}) \, / \, (1 - \nu^2) + 1.1 \, [\nu/(1-\nu)] \, D \tag{6.1}$$

where ε_{pA} = applied maximum horizontal strain, micro strain,

and ε_{qA} = applied minimum horizontal strain, micro strain.

Rewriting the equation results in the maximum excess horizontal stress

$$P_e = P - 1.1 \, [\nu/(1-\nu)] \, D = E \, (\varepsilon_{pA} + \nu\varepsilon_{qA}) \, /(1- \nu^2). \tag{6.2}$$

A similar equation can be developed for the minimum excess horizontal stress

$$Q_e = Q - 1.1 \, [\nu/(1-\nu)] \, D = E \, (\varepsilon_{qA} + \nu \, \varepsilon_{pA}) \, / \, (1- \nu^2). \tag{6.3}$$

Solving equations 6.2 and 6.3 for the strains results in the following equations

$$\varepsilon_{pA} = (P_e - \nu \times Q_e)/E \tag{6.4}$$

and

$$\varepsilon_{qA} = (Q_e - \nu \, P_e)/E. \tag{6.5}$$

The applied strains are then calculated using equations 6.4 and 6.5 with a Poisson's ratio of 0.25. These strain components are the actual strains that are being applied.

6.2 LOCAL STRAIN VARIATIONS

In examining the local strain fields, both the average applied strain for a given site and the standard deviation are determined. The site average strains are calculated from the average excess stresses at each site. The standard deviations are calculated from strains from the individual stress measurements. This standard deviation provides a measure of the variation of the strain field locally. The average and the standard deviations for both the maximum and minimum applied horizontal strains for each site across the eastern United States are given in table 6-1.

Table 6-1. Average applied horizontal strain in the eastern United States by site and by region.

Site	Maximum			Minimum			Elastic modulus, 10^6 psi	Standard deviation	Depth, ft
	Average applied strain, micro strain	Standard deviation	Percent of strain	Average applied strain, micro strain	Standard deviation	Percent of strain			
Central Appalachian Region									
Low Strain									
Beckley #1, hole 2	353	37	10	117	36	31	6.77	0.55	1130
Maple Meadows, hole 6	296	29	10	282	44	16	6.32	0.2	708
Maple Meadows, hole 8	478	90	19	144	14	10	7.09	1.02	1025
Maple Meadows, hole 10	389	65	17	88	29	33	6.92	0.24	807
Beckley #1, hole 15	351	74	21	106	34	32	7.32	0.5	700
Eagle	397	30	8	232	74	32	2.95	0.12	900
Elkhorn #3	316	-		208	-		5.24	-	550
Average	369	61		168	73		6.08		831
Intermediate Strain									
Beckley #4, hole 1	551	-		309	-		1.77	-	820
Pocahontas #4, site 1	631	-	-	317	-	-	3.59	-	1600
Pocahontas #4, site 2	672	66	10	249	83	33	3.25	1.09	1250
Bonny, hole 4	588	151	26	539	139	26	3.59	0.24	1136
Average	611	52	-	354	127	-	2.87	-	1223
High Strain									
Beckley #2, hole 3	703	6	1	354	8	2	2.26	0.07	1100
Bonny, hole 5	827	88	11	248	117	47	6	0.96	1148
Maple Meadows, hole 7	781	322	41	433	222	51	4.44	1.31	735
Maple Meadows, hole 9	967	109	11	543	173	32	2.46	0.08	814
Beckley Mining, hole 11	778	157	20	529	234	44	2.95	0.58	640
Beckley Mining, hole 12	932	43	5	592	70	12	2.94	0.29	870
Beckley Mining, hole 13	861	95	11	494	105	21	2.7	0.24	800
Beckley Mining, hole 14	832	80	10	302	54	18	3.5	0.41	1040
Beckley #2, hole 16	851	63	7	521	23	4	1.72	0.09	350
Average	836	80	-	446	119	-	3.21	1.3	833

Table 6-1. Average applied horizontal strain in the eastern United States by site and by region (Cont.).

Site	Maximum			Minimum			Elastic modulus, 10^6 psi	Standard deviation	Depth, ft
	Average applied strain, micro strain	Standard deviation	Percent of strain	Average applied strain, micro strain	Standard deviation	Percent of strain			
Northern Appalachian Region									
Tanoma, PA	421	-		303	-		5.8		720
Phillippi WV	536	58	11	317	65	21	4.29	2.57	550
Fayette County, PA	519	-	-	191	-	-	11.2	-	400
Barberton, OH	430	-	-	222	-	-	9	-	2300
Southwest, PA, site 1	533	-	-	325	-	-	1.8	-	400
Southwest, PA, site 2	367	30	8	336	25	7	4.4	0.45	700
Southwest, PA, site3	303	67	22	156	19	12	7.65	0.98	800
Average	444	90		264	73		6.31	3.19	838
Eastern Mid-Continent Region									
Wabash, site 1	237	36	15	124	28	22	3.11	0.19	970
Wabash, site 2	341	19	6	80	26	32	2.9	0.25	850
Wabash, site 3[1]	377	28	7	0	1	100	2.85	0.09	860
Monterey	398	107	27	163	50	32	1.67	0.32	290
Galatia[2]	499	36	5	0	0	-	2.96	0.19	570
Peabody #10	533	44	8	71	205	289	2.84	2.47	360
Peabody #2	301	-	-	260	-	-	2.2	-	300
St. Genevieve Limestone	349	-	-	19	-	-	9.32		730
North River, site 1, AL[3]	353	26	7	0	18	-	5.42	0.35	500
Immel, TN	342	130	38	26	42	162	7.96	1.06	925
Jim Walters #7, AL	399	-	-	45	-	-	5.4	1.1	1870
Average	375	87	23	72	85	115	4.24	2.49	748
North River, site 2, AL	173	38	24	0	27	-	4.72	0.35	470
Turris	193	8	4	51	15	29	8.57	0.69	275

[1]The calculated minimum site strain is a -4 micro strains but the minimum site strain is assumed to be zero.
[2]The calculated minimum site strain is a -23 micro strains but the minimum site strain is assumed to be zero.
[3]The calculated minimum site strain is a -68 micro strains but the minimum site strain is assumed to be zero.

For the maximum strain, the standard deviation given in percent of the average strain ranges from 1 to 41 pct of the average while for the minimum strain, the standard

deviation given in percent of the average strain ranges from 2 to 289 pct. There is a wide range in the standard deviations for both components but especially for the minimum strain.

Figure 6-1 shows a histogram of the standard deviation as a percentage of the average strain for the maximum horizontal strain. Although a few sites have a fairly high standard deviation, in general, the standard deviations are less than 24 percent of the average strain. The average standard deviation given in percent of the average strain is only 14 percent while the mode is between 8 and 12 percent.
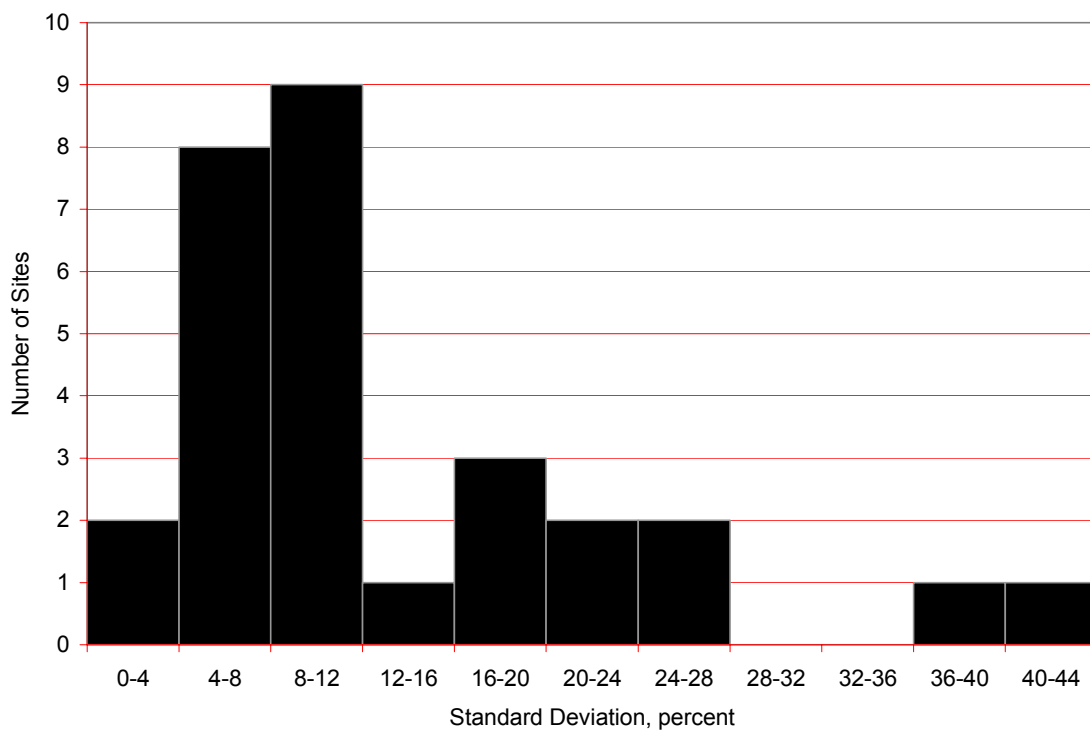
Figure 6-1. Distribution of the standard deviation of the maximum applied horizontal strain given in percent.

Figure 6-2 shows a histogram of the percent of standard deviation of the minimum horizontal strain. In general, the standard deviations are less than 56 percent of the average strain. The average standard deviation given in percent of the average strain is 44 percent with the mode between 24 and 32 percent. However, the outliers increase the average significantly.
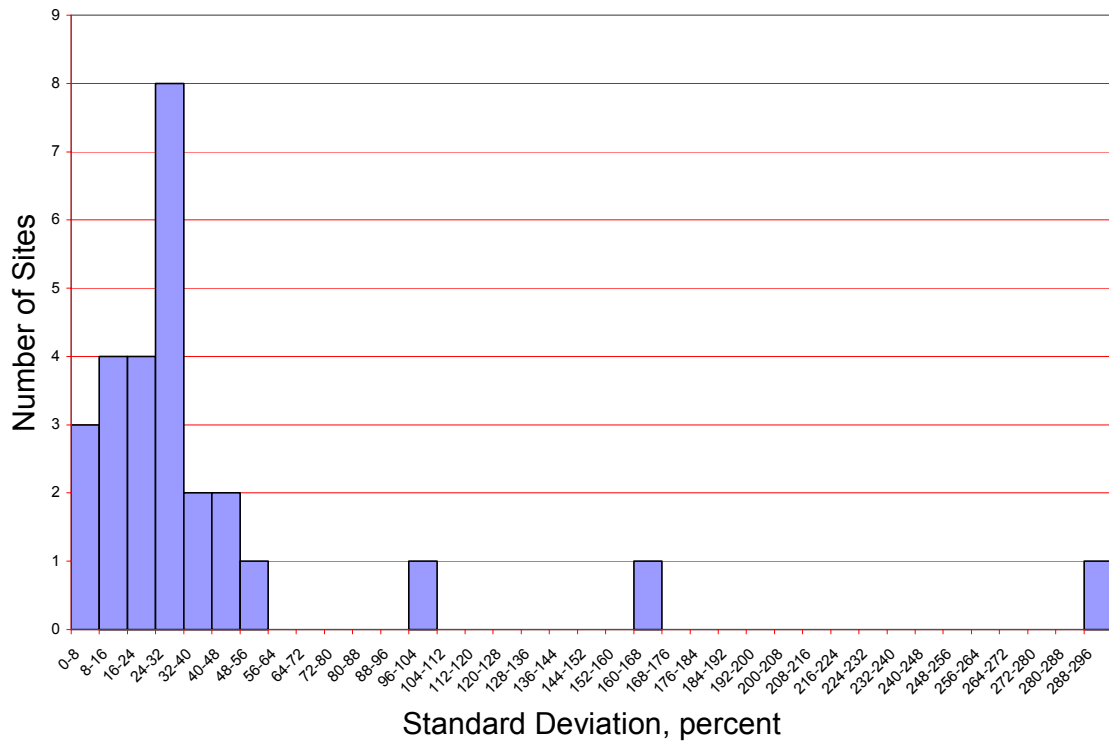
Figure 6-2. Distribution of the standard deviation of the minimum applied horizontal strain given in percent.

In general, the variation in strain is not as large for the maximum horizontal strain as indicated by both the mode and the average standard deviation. The outliers do not have a large effect on the average for the maximum horizontal strain while the majority of the sites have a standard deviation less than 12 percent of the average maximum strain. However, there is a larger range in the standard deviation of the minimum strain while the outliers have a larger effect on the average. The outliers are caused by a combination of low minimum strains and in part higher standard deviations at those sites. The mode for the standard deviations though is clearly higher for the minimum strain. Locally, the maximum horizontal strain is more uniform than the minimum horizontal strain.

The standard deviation reflects the natural variation in the strain field as well as errors in measurements and determination of the elastic properties. Some of the variation could also be due to the influence of mining. These local variations can mask the variations of the stresses due the elastic modulus. Therefore, the range in elastic modulus must be sufficient to overcome these local variations.

Another factor that could influence the results is the distance of the measurements from the opening. The measurements used in the analysis range in depth from 5.2 to 24.8 ft into the roof though only 13 percent of the measurements are less than 10 ft. To determine if there is a significant effect on the individual measurements of the distance from the opening, the applied maximum strains versus the distance from the opening are examined for the eastern United States. Figure 6-3 shows a graph of this data with the measurements separated into high and low strain groups. A linear regression analysis is performed on each data set. The coefficients for the distance are for the low strain group 2.4 micro strains/ft and for the high strain group 7.7 micro strains/ft indicating that the strain does appear to increase by a small amount with distance from the opening. However, the coefficients of determination of 0.01 and 0.05 indicate there is no correlation between the distance from the opening and the maximum applied strain while the coefficients for the distance developed from the regression analysis are not significantly greater than zero. Therefore, the strains do not appear to increase significantly with distance from the opening indicating that the distance from the opening appears to have a minimal influence on the measurements and should have minimal affect on the results from the analysis of this data set.
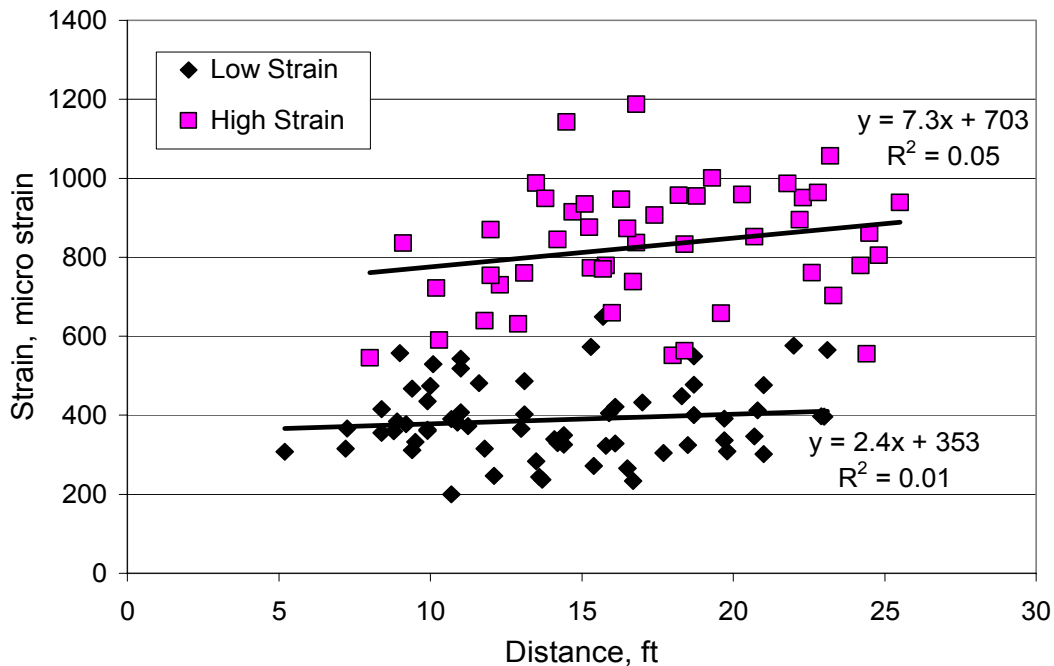
Figure 6-3. Maximum applied horizontal strain versus distance of the measurement from the opening, eastern United States.

6.3 REGIONAL STRAIN VARIATIONS

To evaluate the regional strain variations, the applied horizontal strains are examined with the analysis of the strains based on three regions, the eastern Mid-Continent region, and the northern and central Appalachian regions. The approximate regional boundaries based on site groupings is given in figure 6-4. Table 6-2 shows the average maximum and minimum applied horizontal strain and the standard deviation for each region. The following analysis for each region is based on the average strains determined at each site (table 6-1).
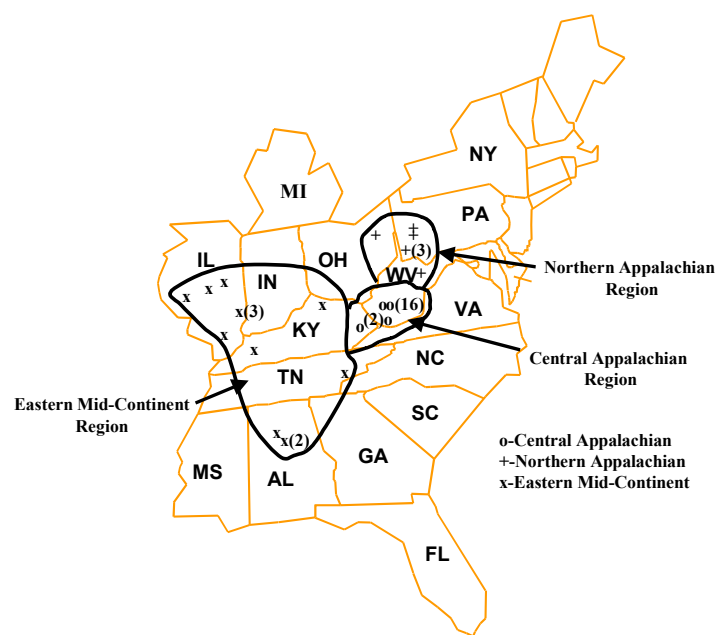
Figure 6-4. Approximate regional boundaries based on site groupings.

Table 6-2. Applied horizontal strain by region for the eastern United States.

Zone	Maximum strain, micro strain	Standard deviation	Range of site maximum strain, micro strain	Minimum strain, micro strain	Standard deviation	Strain ratio max/min
Northern Appalachian						
	444	90	303-536	264	73	1.68
Central Appalachian						
Low	368	60	296-478	168	73	2.2
Intermediate	611	52	551-672	354	127	1.73
High	836	81	703-967	439	116	1.89
Eastern Mid-Continent						
	375	80	156-533	72	81	5.29

6.3.1 Eastern Mid-Continent Region

The maximum applied horizontal strain by site ranges from 173 to 533 micro strains with a standard deviation that is 21 percent of the average strain. Figure 6-5A shows a histogram of the average maximum horizontal strain from each site. The mode is between 300 and 400 micro strains with 8 of the 13 sites within this range.

The average regional maximum strain of 375 micro strains also falls within this range. The low strain Turris and North River site 2 sites however, are not included in the average strain calculations though the sites are included on the histogram. The Turris measurements are not very deep into the roof and are probably under the influence of the opening. Further, the Turris Mine is also the shallowest site and may be influenced by near surface stress relief effects from glacial filled bedrock valleys. At the North River Mine in Alabama, site 2 appears to be influenced by the normal fault located 600 ft from the site. The average site strain is only 173 micro strains. These sites are also excluded from the general analysis. Without the Turris and the North River site 2, the site strains range from 238 to 533 micro strains. Further, the Wabash site one, has an average strain of 238 micro strains. However, this site is near a fault that appears to have reduced the strain level locally. The other two sites in the Wabash mine have maximum strains of 341 and 377 micro strains. Excluding the Wabash site one, the average maximum regional strain is 388 micro strains.

Figure 6-5B shows a histogram of the minimum horizontal strain. The minimum strain ranges from 0 to 260 micro strains with an average strain of 72 micro strains. However, the standard deviation is 118 pct of the average minimum strain. The minimum strain for the Turris and North River site 2 are not outliers in this case. Most of the sites have a minimum applied strain that is less than 100 micro strains.

6.3.2 Northern Appalachian Region

In this region, the maximum horizontal strain by site ranges from 303 to 536 micro strains with a standard deviation that is 20 percent of the average strain. Figure 6-6A shows a histogram of the maximum horizontal strain for each site. The strains are distributed fairly evenly across the range.
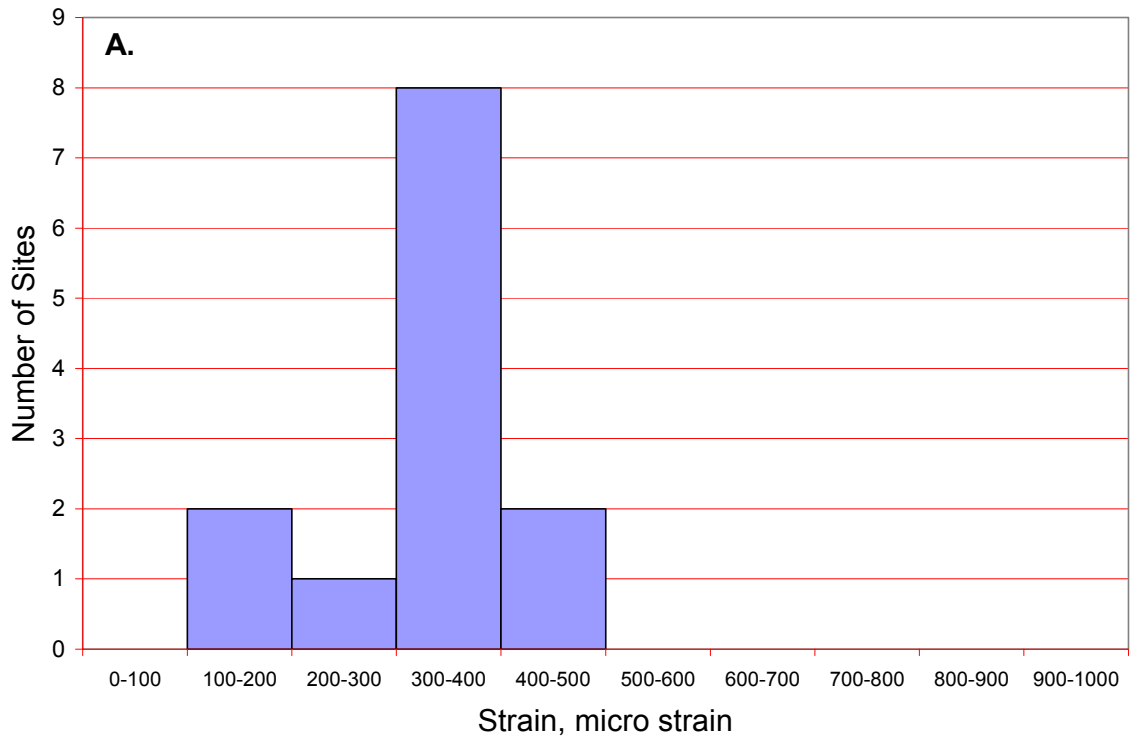
Figure 6-5A. Distribution of the applied horizontal strain in the eastern Mid-Continent region, maximum.
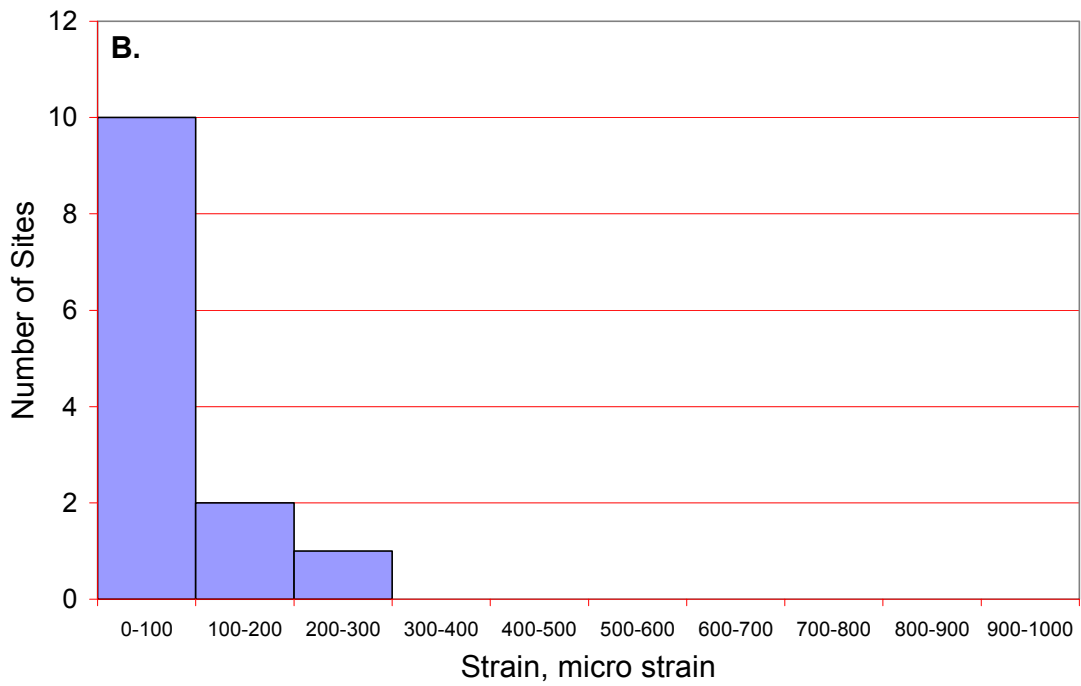
Figure 6-5B. Distribution of the applied horizontal strain in the eastern Mid-Continent region, minimum.
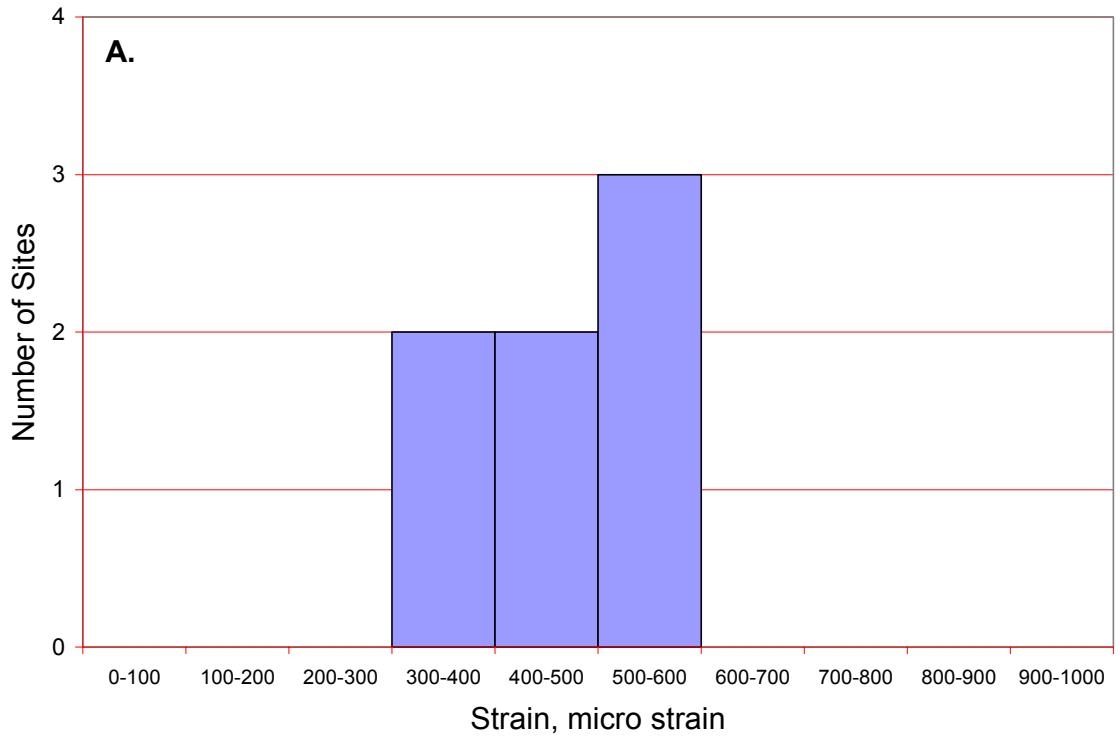
Figure 6-6A. Distribution of the applied horizontal strain in the northern Appalachian region, maximum.
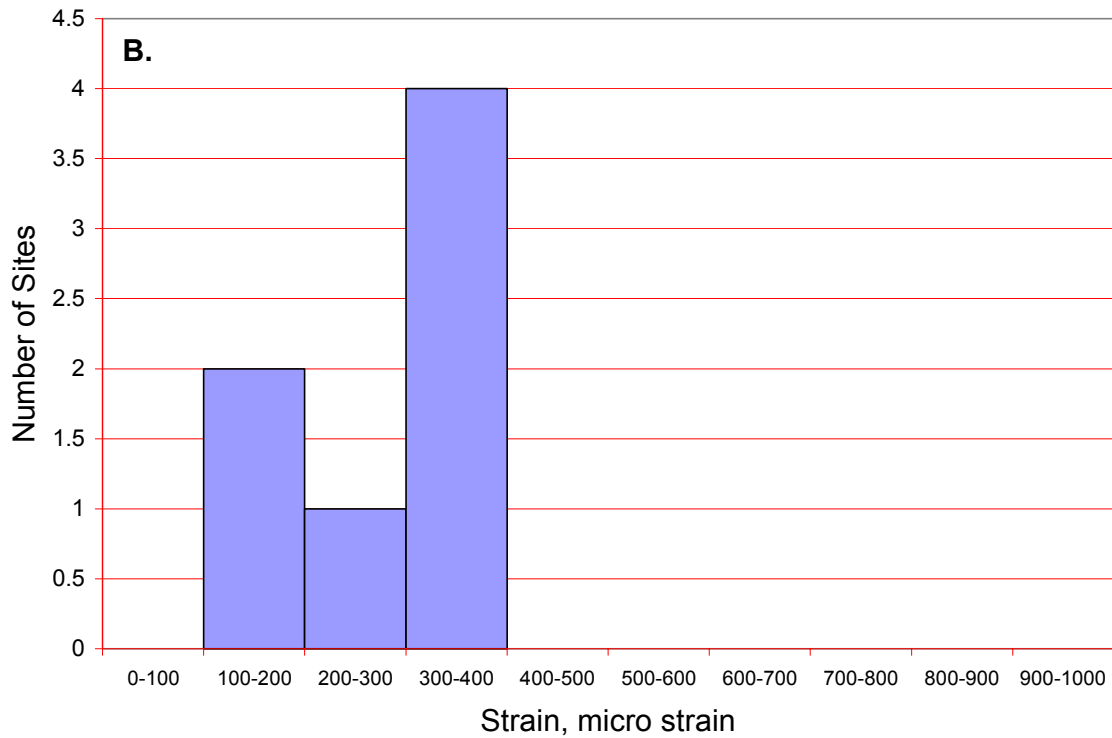
Figure 6-6B. Distribution of the applied horizontal strain in the northern Appalachian region, minimum.

The minimum strain ranges from 156 to 336 micro strains with a standard deviation that is 28 percent of the average strain. Figure 6-6B shows a histogram of the minimum strain distribution across the region. The histogram indicates that for the majority of the sites, the minimum strains are between 300 to 400 micro strains.

6.3.3 Central Appalachian Region

In the central Appalachian region, the maximum horizontal strain ranges from 296 to 967 micro strains. This reflects the low and high strain zones that have been identified in the region. Figure 6-7A shows a histogram of the average maximum horizontal strain from each site. The distribution is bimodal indicating the existence of both low and high strain zones within the region. The lower strain region includes the low strain sites in the Beckley, Elkhorn #3 and Eagle seams with strains below 500 micro strains and the high strain region includes the high strain sites in the Beckley seam with strains above 700 micro strains. There also appears to be a third intermediate strain zone that includes the Sewell, Pocahontas #4 seam sites and one Beckley seam site (table 6-1). The third or intermediate zone of strain can be designated between 550 to 700 micro strains.

Although there is a substantial variation of strains across the region, the strain variation within each strain zone is much less. For the high strain zone, the maximum strain ranges from 703 to 967 micro strains with a standard deviation that is 10 percent of the average strain. The distribution indicates that the largest number of sites have an average strain of between 827 to 967 micro strains. For the low strain zone, the strain ranges from 296 to 478 micro strains with a standard deviation that is 17 percent of the average strain. Most of the strains fall between 316 to 397 micro strains. For the intermediate strain zone, the strains range from 551 to 672 micro strains with a standard deviation that is 9 percent of the average strain

. The minimum applied horizontal strain ranges from 88 to 592 micro strains. Figure 6-7B shows a histogram of the average minimum strain. The distribution is not as clear as the maximum strain distribution in indicating two or possibly three strain zones. Further, there is some overlap between the low, intermediate and high strain zones as designated by the maximum strain. For the high strain region, the strain ranges between 248 to 592 micro strains with a standard deviation that is 28 percent of the average. For

the low strain zone, the average strain ranges from 88 to 282 micro strains with a standard deviation that is 43 percent of the average strain. For the intermediate zone, the average strains range from 249 to 539 micro strains with a standard deviation that is 36 percent of the average minimum strain.
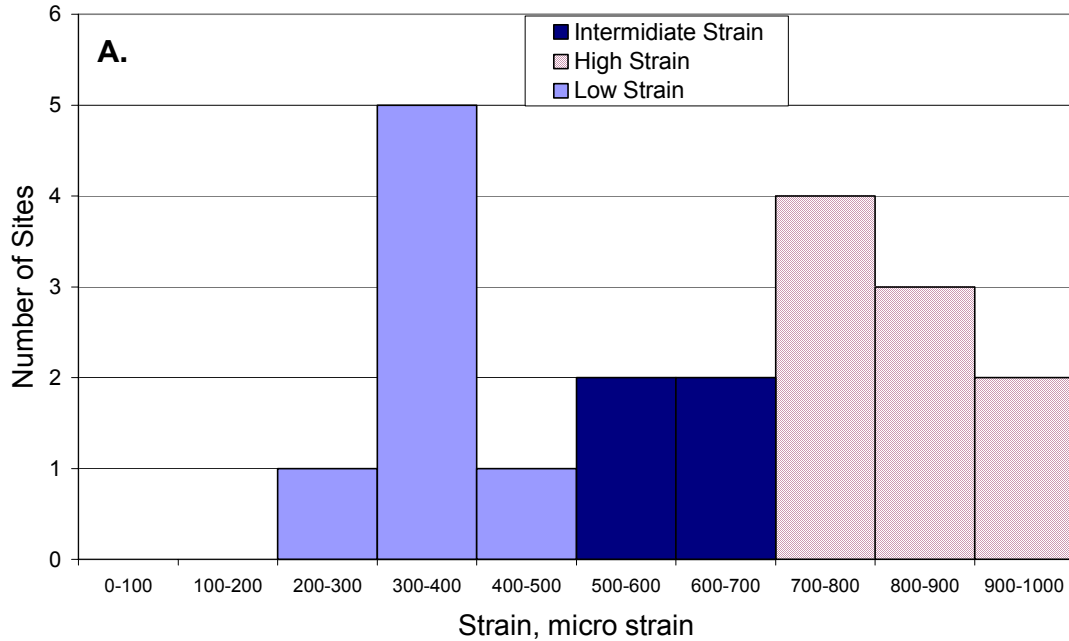
Figure 6-7A. Distribution of the applied horizontal strain in the central Appalachian region, maximum.
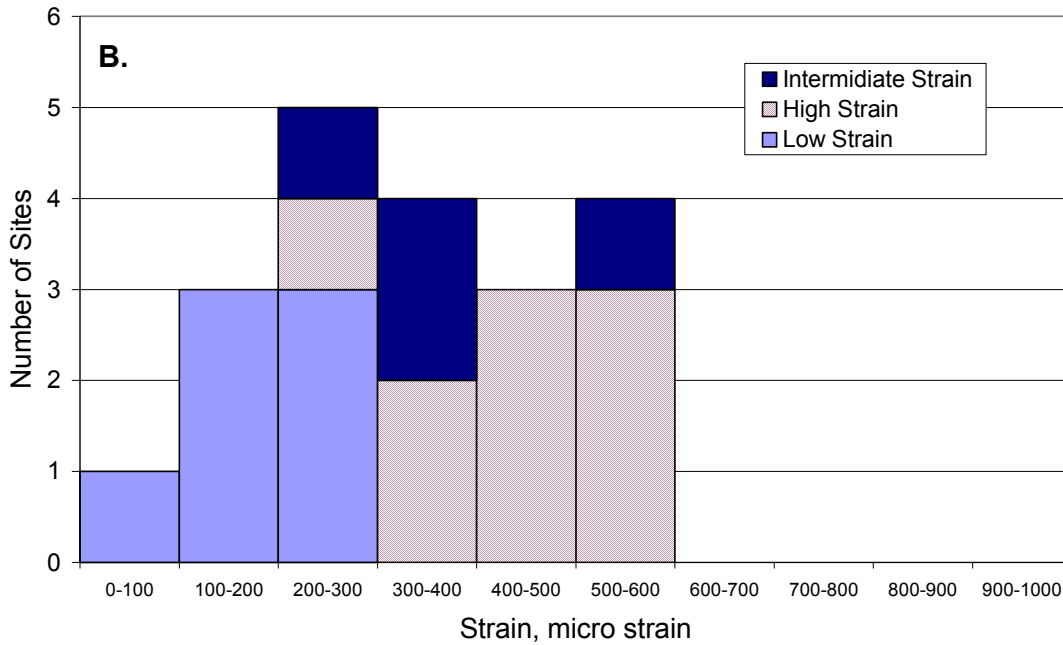
Figure 6-7B. Distribution of the applied horizontal strain in the central Appalachian region, minimum.

There are high and low strain sites in the central Appalachian region and except for the Beckley seam the geographic distribution is not clear. The high strain sites include sections of the Beckley seam and possibly sites in the Sewell and Pocahontas #4 seams. In the Beckley seam, all but two of the high strain sites are in a coterminous area of several hundred square miles. All the low strain sites in the Beckley seam are in an adjacent area encompassing tens of square miles. The other low strain sites in the region are somewhat isolated from the Beckley seam. To develop a clearer outline of the geographic distribution of the strain field across the region will require more stress measurements. However, if a reason for the existence of the high and low strain fields can be deduced, a better understanding of the strain patterns for the region could be developed.

A possible cause of the two or three strain fields could be the strength of the rock mass or faults. Essentially, the magnitude of the maximum horizontal stress is limited by the rock mass or fault strength (Zoback et al., 2003). An important parameter in this concept is the confinement or minimum stress. With increasing confinement, the rock mass or fault strength also increases thus being able to withstand higher maximum horizontal stresses.

The possible affects of the strength limiting the stress magnitude can be seen with the Beckley seam data where the high and low strain sites group into distinct geographic zones. For the high strain zone in the Beckley seam excluding the Beckley #2 sites, the average maximum horizontal stress is 3,800 psi. For the five sites in the low strain zone, the average maximum horizontal stress is 3,300 psi. Further, in the Beckley seam, the minimum or confining stress is the vertical stress. For the 8 high strain sites used in this analysis, the average site depth is 900 ft while for the 5 low strain sites, the average site depth is 875 ft. Essentially, both zones have approximately the same vertical or confinement stress that could result in similar rock mass or fault strengths and therefore result in about the same maximum horizontal stress magnitude. The average maximum horizontal stresses for the two zones are within 15 percent.

The average elastic modulus for the low strain zone sites is 6.9 million psi and for the high strain zone sites, 3.6 million psi. Based on the average elastic modulus and maximum horizontal stress for each zone, the average horizontal strain from the

maximum horizontal stress for the high strain zone is 1060 micro strains and for the low strain zone 480 micro strains. Essentially, strength limits the maximum horizontal stress in both zones to approximately the same magnitude while the much higher elastic modulus in the low strain zone results in the much lower strain field.

6.3.4 Summary of Regional Strain Fields

The regional average maximum applied horizontal strain ranges from 369 to 836 micro strains with the lowest and highest regional strains found in the central Appalachian region. The minimum average strain ranges from 72 to 440 micro strains. The lowest is found in the eastern Mid-Continent region and the highest in the high strain zone of the central Appalachian region.

As with the local strain fields, the regional strain fields are not completely uniform. However, the regional strain fields appear to be sufficiently uniform except for the central Appalachian region to allow for the development of adequate regression models between the maximum horizontal stress and the elastic modulus of the rock. Regionally, for the maximum applied strain, the standard deviation in percent of the average strain varies from only 10 to 21 percent. Further, the range of the site averages for a region or zone is less than 270 micro strains. Therefore, the regional average strains, standard deviations and range of strains can be used to determine or estimate the horizontal strains and stresses that may occur elsewhere within the region. Essentially, the measurements are a sampling of the stress and strain field across a region. The exception is the central Appalachian region where the geographic demarcation of the zones is not clear.

The minimum strain shows more variation as indicated by equal or higher standard deviations than those for the maximum strain. This results in the standard deviation being a much higher percent of the minimum average strain.

6.3.5 Comparison of Regional Strain Fields

Clearly, the central Appalachian region has areas with substantially higher maximum applied strains than the other regions. Except for the central Appalachian region, the other regions appear to have similar maximum horizontal strain fields. For two of the regions, the northern Appalachian region and the eastern Mid-Continent

region, the average maximum applied regional strains are within 70 micro strains. Even the low strain zone of the central Appalachian region has an average maximum strain that is only 8 micro strains below that of the eastern Mid-Continent region. However, for the low strain zones, the average regional strain in the northern Appalachian region is about 20 percent higher than the other two regions.

Table 6-3. Statistical comparison of selected regional average maximum applied horizontal strains.

Regional comparison	t-statistic	Degrees of freedom	Significant difference
Northern Appalachian vs. Eastern Mid-Continent	1.64	16	No
Northern Appalachian vs. Central Appalachian (low strain zone)	1.85	10	No
Northern Appalachian vs. Central Appalachian (high strain zone)	8.9	12	Yes
Central Appalachian (high strain zone) vs. Central Appalachian (low strain zone)	13.1	14	Yes

Table 6-3 gives a statistical comparison between the regional maximum strain averages. Even though the northern Appalachian region has a higher strain, statistically there is no significant difference between the northern Appalachian, eastern Mid-Continent and central Appalachian low strain zone regional maximum strain. The maximum strain in the central Appalachian high strain zone is significantly higher than any of the low strain zones. Essentially, the central Appalachian high strain zone does have a significantly higher maximum applied strain than any other region.

There is a somewhat larger difference in the minimum average strains between the low strain zones. The eastern Mid-Continent region has a lower minimum strain and a more biaxial strain field than the northern and central Appalachian regions while the northern Appalachian region has minimum strains that are higher than those in the central Appalachian low strain zone. The highest minimum strains are found in the intermediate and high strain zones of the central Appalachian region followed by the northern Appalachian region. However, there is less difference between the minimum strain in the central Appalachian region for all three zones and the northern Appalachian region than

for the maximum strain. The strain fields in these regions are less biaxial than the eastern Mid-Continent region.

The eastern Mid-Continent region encompasses a very large area of the eastern United States and has a fairly uniform applied maximum strain, however, the strain field is very biaxial with a maximum to minimum strain ratio of 5.3.   In the northern Appalachian region the maximum strain is about 20 percent higher though the strain field is less biaxial with a ratio of only 1.68. The northern Appalachian strain region is smaller than the eastern Mid-Continent region but still fairly large. Clearly, the intermediate and high strain zones of the central Appalachian region have the highest maximum applied strains.   However, the distribution of the strain fields in this region is much more complex though this distribution appears to still be geographic. Geographically, the high and low strain zones in the Beckley seam appear to only cover tens or hundred of square miles.

6.4 STRAIN VARIATION ACROSS THE EASTERN UNITED STATES

Figure 6-8A shows a histogram of the maximum applied horizontal strain by site across the eastern United States. Twenty-four of the 38 sites have a maximum strain between 300 and 550 micro strains with 26 sites between 300 and 600 micro strains. These sites are spread across all the main geographic regions. Therefore, the typical maximum strain field across the eastern United States appears to have a magnitude between 300 to 600 micro strains. This range is somewhat broadened because of the strains in the northern Appalachian region being about 20 percent higher than those in the other low strain regions. Further, for both the eastern Mid-Continent and low strain central Appalachian regions, the maximum strains are concentrated at the mode between 300 to 400 micro strains with only one or two sites for each region between 400 and 550 micro strains. The strains between 550 to 700 micro strains are all in the central Appalachian region.

From the histogram, the maximum strain field is skewed with only three sites well below 300 micro strains. Since the mode is between 300 and 400 micro strains with these strains from all the regions as well as from a range in depths that are not subject to near surface strain relief, those strains in the eastern United States that fall below about

300 micro strains may have been to some degree subject to strain relief. Two sites, both in the eastern Mid-Continent region are below 200 micro strains, the Turris Mine and North River site 2. The Wabash mine, site one is also below 300 micro strains. The Wabash and North River site 2 were near faults that could have resulted in some strain relief. The Turris Mine is the shallowest site at 275 ft in a region with bedrock valleys that are filled with unconsolidated material. Essentially, the distribution is skewed because the strains cannot realistically fall below zero and the location of the mode indicates that those strains below about 300 micro strains are possibly in partial strain relief.

From the histogram, the distribution is spread out toward the right because of the high strain zone in the Beckley seam and the other intermediate sites in the central Appalachian region. The number of sites in the high strain zone is due to increased sampling in this zone and therefore the distribution does not represent the true geographic extent of the high strain zone that appears to be geographically limited. Because of ground control problems, there was a concentration of stress measurements made in the seam. What this distribution indicates is that there is a high strain zone but not the extent of that zone.

Figure 6-8B shows a histogram of the minimum applied horizontal strains across the eastern United States. Most of the sites (22) have strains between 100 to 400 micro strains. Eleven of the sites have strains that are below 100 micro strains with ten of the sites found in the eastern Mid-Continent region. This reflects the low minimum horizontal stresses found in the region. All the sites with strains above 400 micro strains are again found in the Beckley seam and central Appalachian region. However, although the distribution is again skewed, it is not as well defined as that for the maximum horizontal strain.
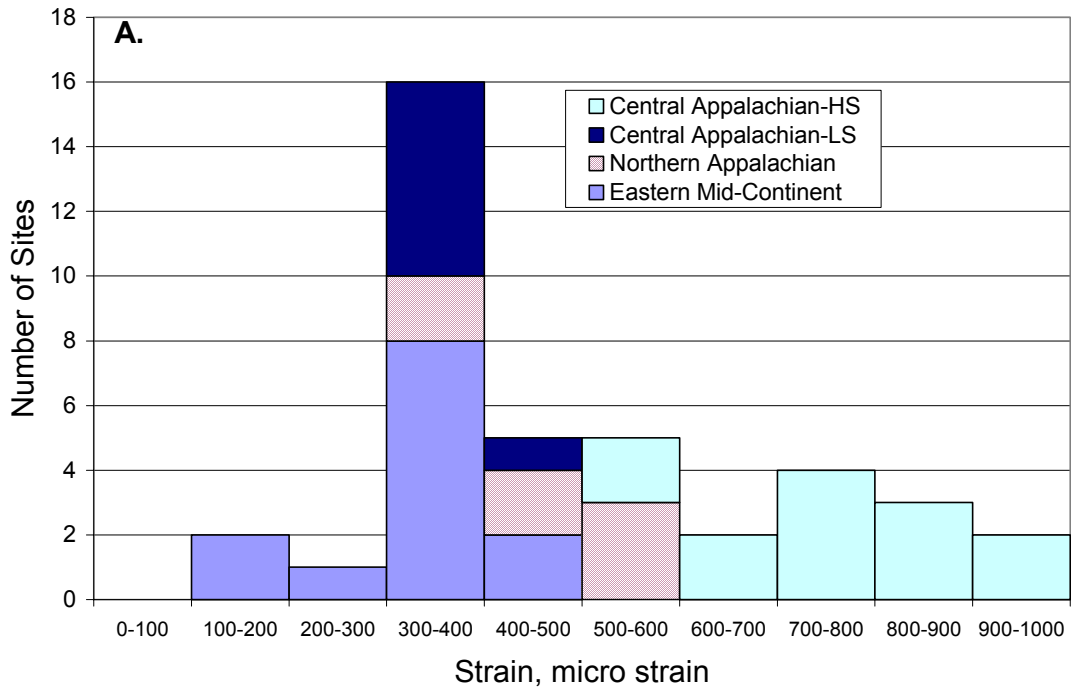
Figure 6-8A. Distribution of the applied horizontal strain across the eastern United States, maximum.
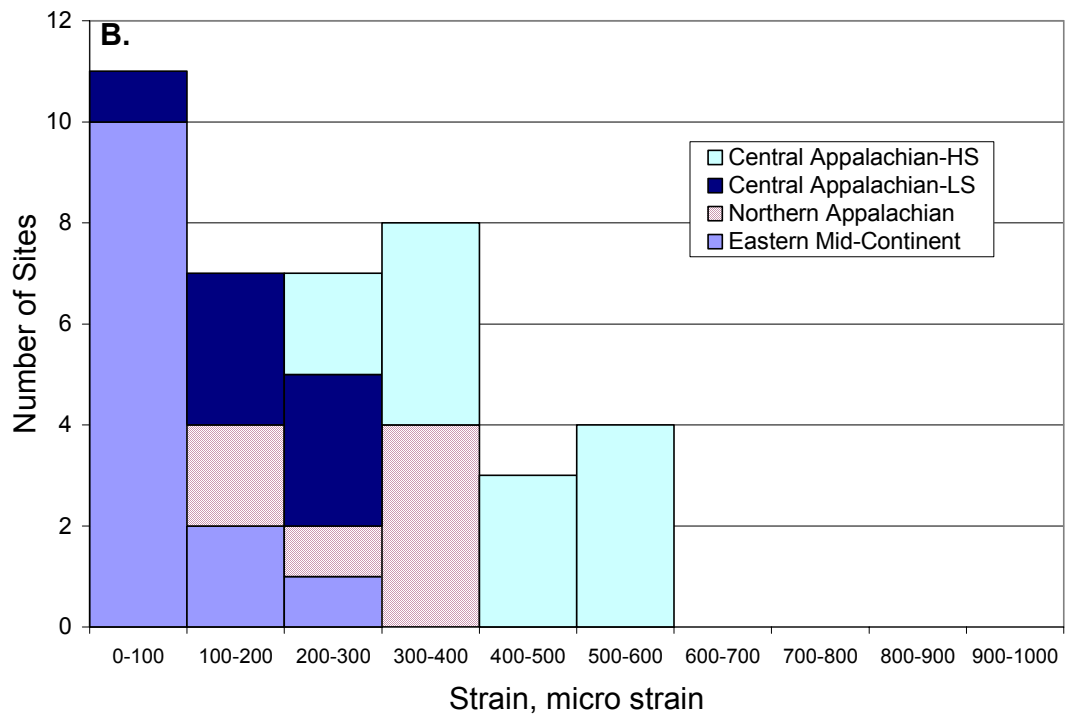
Figure 6-8B. Distribution of the applied horizontal strain across the eastern United States, minimum.

6.5 REGIONAL STRAIN VARIATION-CONCLUSIONS

Locally, the maximum applied horizontal strains are fairly uniform with an average standard deviation that is 14 percent of the average site strain. The minimum applied horizontal strains are much more variable with an average standard deviation that is 44 percent of the average site strain.

Distance of a measurement from the opening is not a significant factor in the variation of the applied maximum horizontal strain. Therefore, the distance of the measurement from the opening appears to have minimal influence on the results.

Based on the maximum applied horizontal strains, the eastern United States can be separated into three regions that include the eastern Mid-Continent region, the northern Appalachian region and the central Appalachian region. The central Appalachian region is further divided into high and low strain zones. The regional or zonal maximum applied strains are fairly uniform with standard deviations that are between 9 and 21 percent of the regional average.

The regional averages for the maximum applied horizontal strains are not significantly different for the northern Appalachian region, eastern Mid-Continent region and the central Appalachian low strain zone though the north Appalachian region has strains that are about 20 percent higher.

There is a high strain zone in the central Appalachian region with maximum applied horizontal strains that are significantly higher than any other region.

The applied horizontal minimum strains are lowest in the eastern Mid-Continent region. This results in much more directional or biaxial horizontal strain and stress fields in this region as compared to the other regions.

The typical average maximum applied horizontal site strain in the eastern United States is between 300 and 600 micro strains.

CHAPTER 7: REGIONAL AND LOCAL STRESS AND STRAIN MODELS

In general, the linear relationship between the stress and the elastic modulus should be strongest locally or at a specific site where the strains would show more uniformity with the stresses then varying with the elastic modulus. However, the limitation of the local or site analysis is that the range in the elastic modulus may not be sufficient to establish a reliable model. For the individual mines and seam analysis, the individual measurements are used.

A more general horizontal stress model that encompasses larger geographic regions that examines the relationship between the horizontal stress, the elastic properties and depth can also be developed. Over the larger regions, the variation of the elastic modulus may be sufficient to establish a regional model. However, any larger geographic region must have a sufficiently uniform strain field where the relationship that exists between stress, strain and the elastic modulus is not masked by the variation in the strain field. Three larger areas are examined that include the northern and central Appalachian regions and the eastern Mid-Continent region. Based on the previous strain analysis, both the northern Appalachian and eastern Mid-Continent regions appear to have sufficiently uniform strain fields. The strain field is more complex in the central Appalachian region so the analysis is separated into high and low strain zones. For the regional analysis, the average site stresses are used.

7.1 REGIONAL STRESS AND STRAIN MODELS

Regional models are developed for the northern Appalachian and eastern Mid-Continent regions as well as the high and low strain zones for the central Appalachian region. Regression models are presented for the horizontal stresses with respect to the elastic modulus and depth for each region while the excess stresses and strains from the maximum horizontal are also considered.

7.1.1 Variation of the Horizontal Stress with the Elastic Modulus

To evaluate the variation of the horizontal stress with the elastic modulus, a regression analysis using equation 3.1 is conducted on the data for each region.

Figure 7-1 shows graphs of the maximum horizontal stress versus the elastic modulus for each region. Table 7-1 shows the resulting regression coefficients, constants and coefficients of determination from the regression analysis.

Table 7-1. Regional regression models for the maximum horizontal stress versus the elastic modulus.

Model	Number of sites	Coefficient, K_1	Constant, K_2	Coefficient of determination, R^2
Central Appalachian Region				
Low strain	7	444	252	0.72
High strain	13	965	215	0.9
Northern Appalachian Region				
General	7	576	0	0.89
General	7	564	94	0.89
Eastern Mid-Continent Region				
General[1]	11	445	0	0.87
General[1]	11	375	393	0.91
General[2]	13	292	564	0.65

[1]Regression analysis without the Turris Mine, Illinois and the North River mine site 2.
[2]Regression analysis with all the site data.
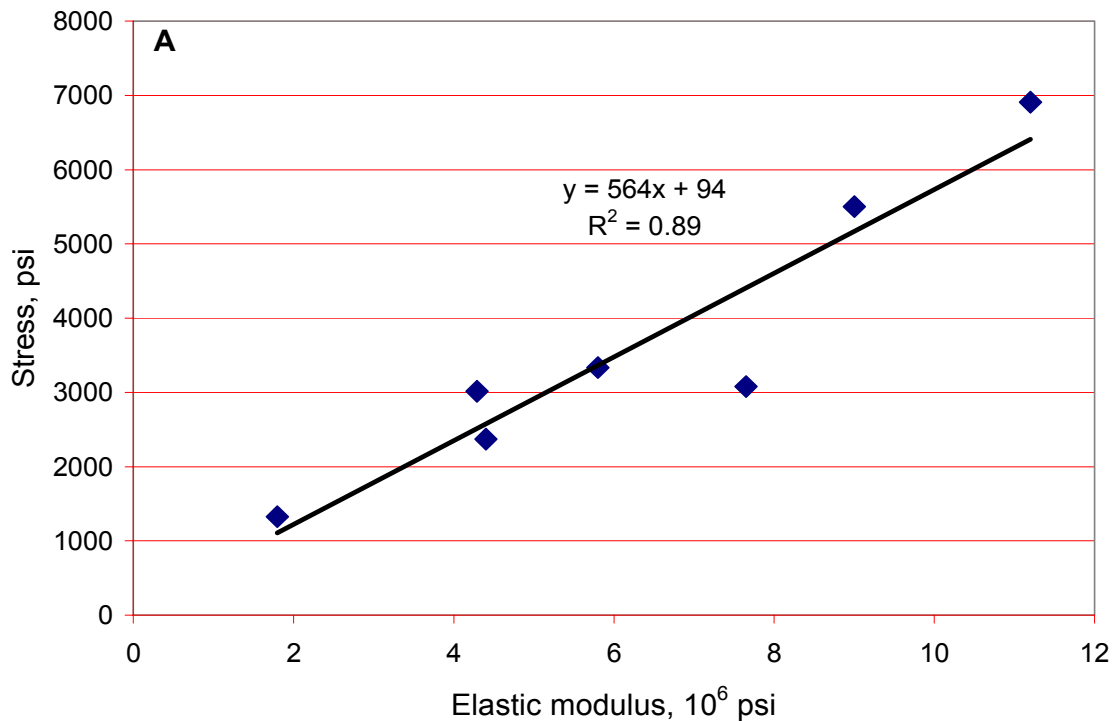
Figure 7-1A. The maximum horizontal stress versus the elastic modulus, northern Appalachian region.
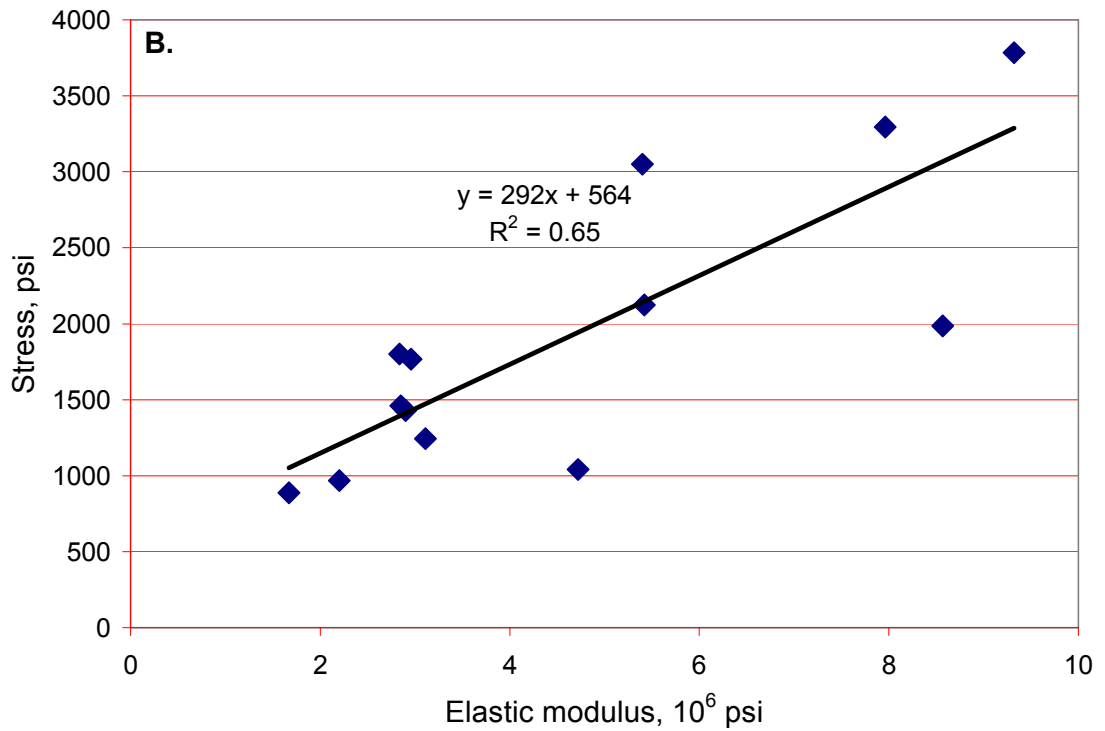
Figure 7-1B. The maximum horizontal stress versus the elastic modulus, eastern Mid-Continent region (with the Turris and North River sites).
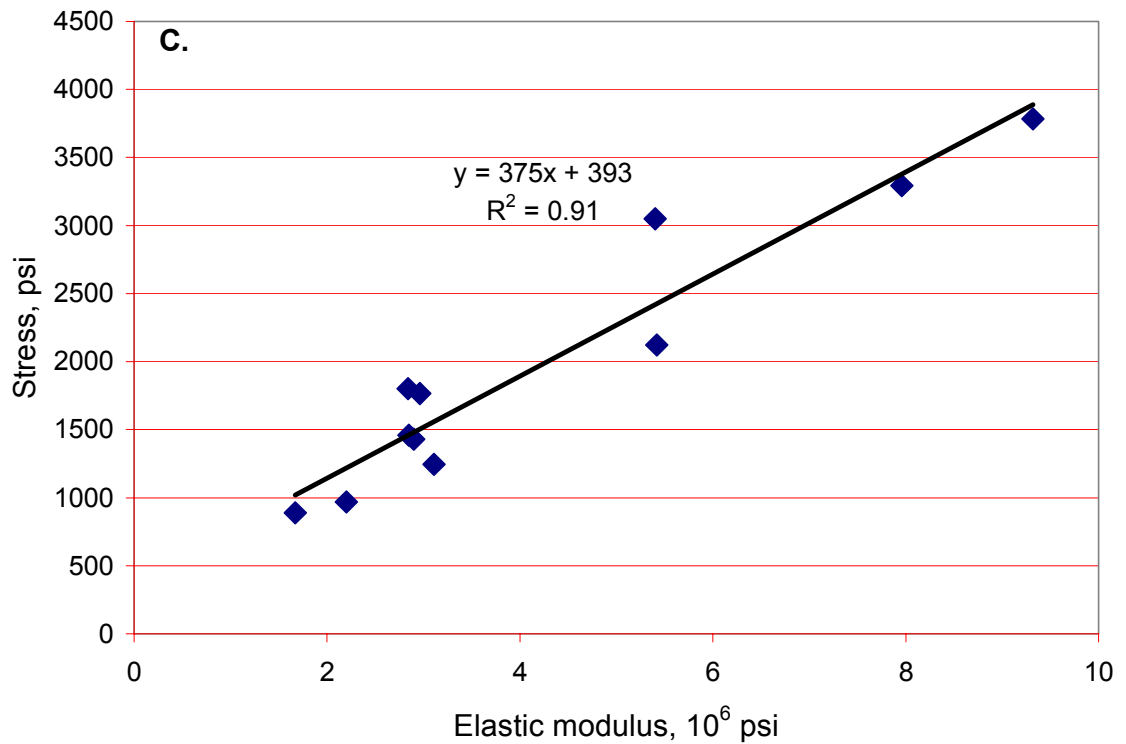
Figure 7-1C. The maximum horizontal stress versus the elastic modulus, eastern Mid-Continent region (without the Turris and North River sites).
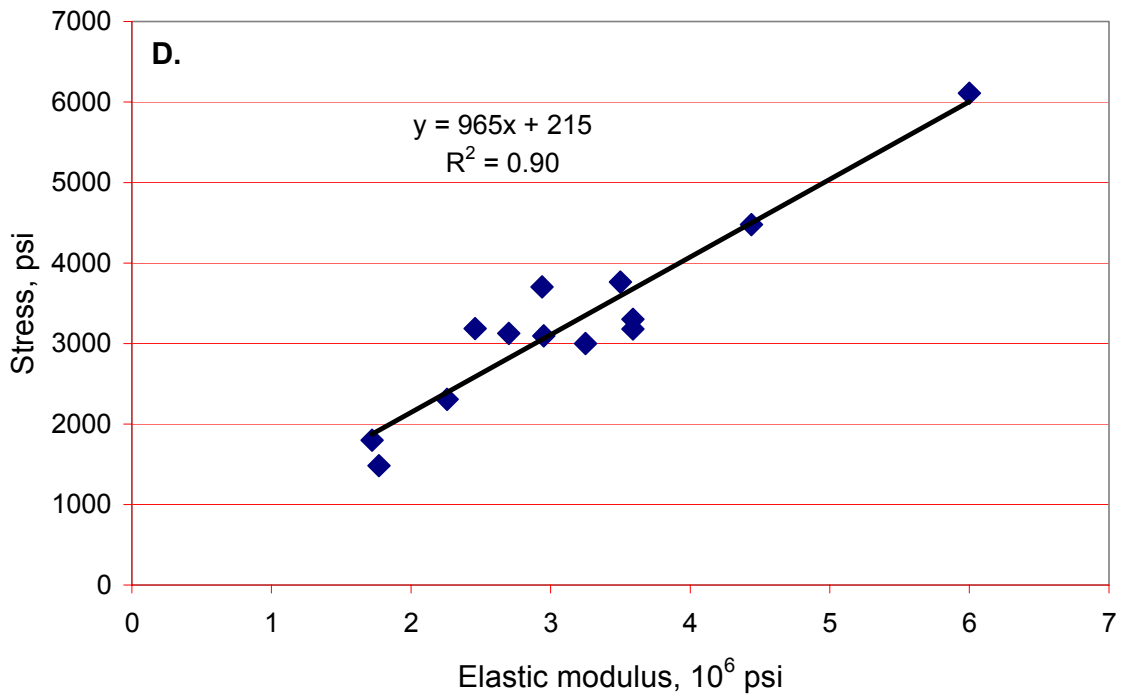
Figure 7-1D. The maximum horizontal stress versus the elastic modulus, central Appalachian region (high strain zone).
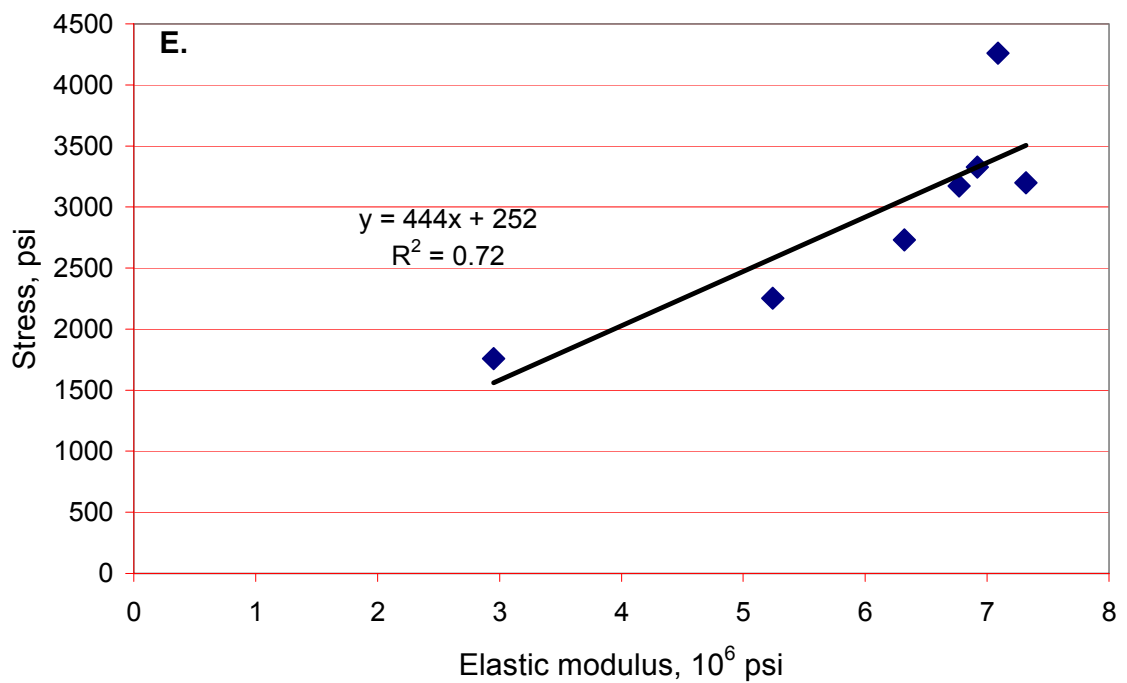
Figure 7-1E. The maximum horizontal stress versus the elastic modulus, central Appalachian region (low strain zone).

The coefficients of determination identifies how much of the variation of the maximum horizontal stress can be explained by the elastic modulus. The models can explain from 72 to 91 percent of the variation. The highest correlation is found in the eastern Mid-Continent region with the lowest in the central Appalachian region low strain zone. The lower correlation in the central Appalachian low strain zone results from the grouping and limited distribution of the elastic modulus where only one site elastic modulus was below 5 million psi. Again, this reflects what was observed with the Beckley seam analysis. In the case of the eastern Mid-Continent and northern Appalachian regions, the regression fit is also forced through zero with little reduction in the fit.

For the eastern Mid-Continent region, with all the sites, the coefficient of determination is only 0.65. Examining the strain data reveals that two sites, the Turris Mine and North River site 2 have strains that are much lower than the other sites. Based on previous discussions, the sites may be partially strained relieved. The average strain from the maximum horizontal stress at Turris is only 232 micro strains and at the North River site 2, only 221 micro strains. Without these sites, the range of strain from the maximum horizontal stress is from 400 to 633 micro strains.

Without the Turris Mine and North River site 2, the coefficient of determination is 0.91 for the eastern Mid-Continent region. The coefficient of determination has increased substantially without the two low strain sites. It is not only the low strains for these sites but also the high elastic modulus for the Turris Mine that affects the results of the regression analysis for the maximum horizontal stress. Therefore, because of substantially lower strains, these two sites are excluded from all further analysis of the eastern Mid-Continent region.

For the high strain zone of the central Appalachian region, the equation and coefficient of determination are close to that obtained for the Beckley seam. However, for the low strain zone, the coefficient of determination of 0.72 is much higher than for just the Beckley seam and reflects the increased range of the elastic modulus.

Figure 7-2 shows graphs of the minimum horizontal stress versus the elastic modulus for each region. For the minimum horizontal stress in each region, equation 3.1

is used for the regression analysis. Table 7-2 shows the resulting regression coefficients, constants and coefficient of determination for the minimum horizontal stress.

The coefficient of determination ranges form 0.25 to 0.81 and is in general much less than for the maximum horizontal stress. However, the northern Appalachian region and central Appalachian high strain zone have correlations that are fairly good. For these regions, the variation of both the maximum and minimum horizontal stress can be explained to a large extent by the elastic modulus of the rock. The poor fit in the eastern Mid-Continent region is due to the low average minimum strain and the relatively high standard deviation of the strain that is larger than the average strain. In the central Appalachian low strain zone, the poor fit is due to the limited range of the elastic modulus, the lower average minimum strain and the relatively high standard deviation.

Table 7-2. Regional regression models for the minimum horizontal stress versus the elastic modulus based on site average stresses.

Model	Number of sites	Coefficient K_1	Constant K_2	Coefficient of determination R^2	Stress ratio, max/min	Standard deviation of ratio	Range of ratio
Central Appalachian Region							
Low strain	7	141	1072	0.25	1.55	0.36	1.03-2.01
High strain	13	490	789	0.67	1.39	0.2	1.05-1.84
Northern Appalachian Region							
General	7	298	762	0.81	1.34	0.21	1.05-1.74
General	7	397	0	0.7	1.34	0.21	1.05-1.74
Eastern Mid-Continent Region							
General[1]	11	90	480	0.35	2.59	1.66	1.08-7.15

[1]Without the Turris Mine, Illinois and the North River site 2, Alabama
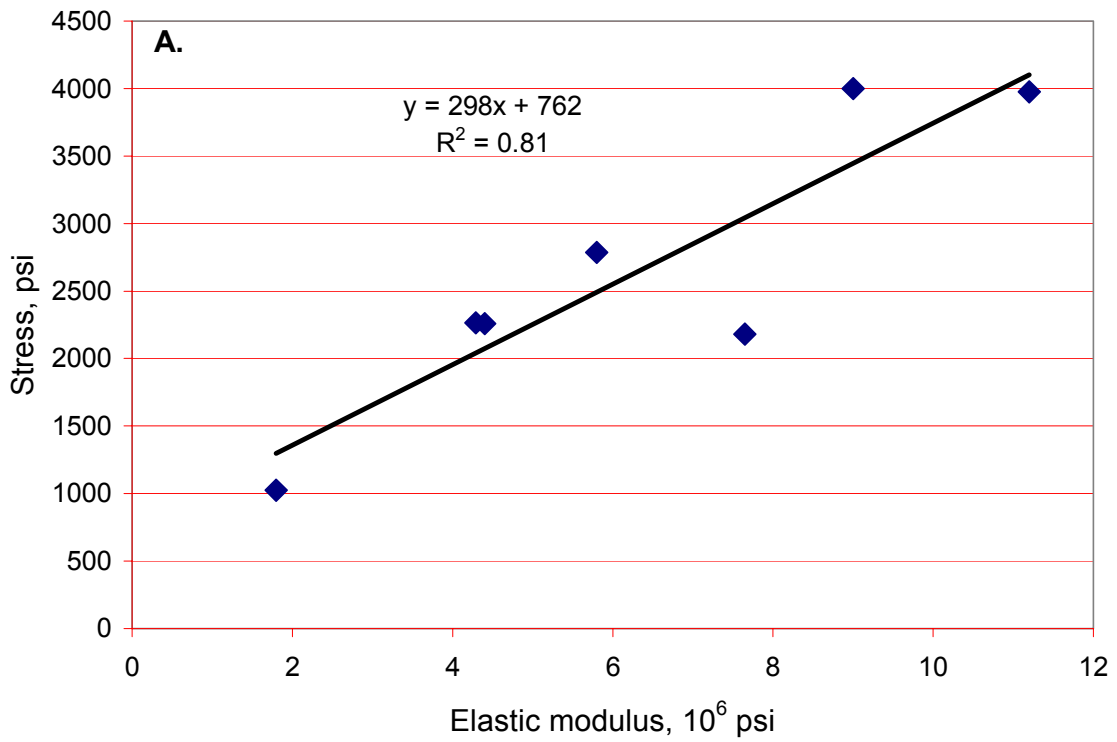
Figure 7-2A. The minimum horizontal stress versus the elastic modulus, northern Appalachian region.
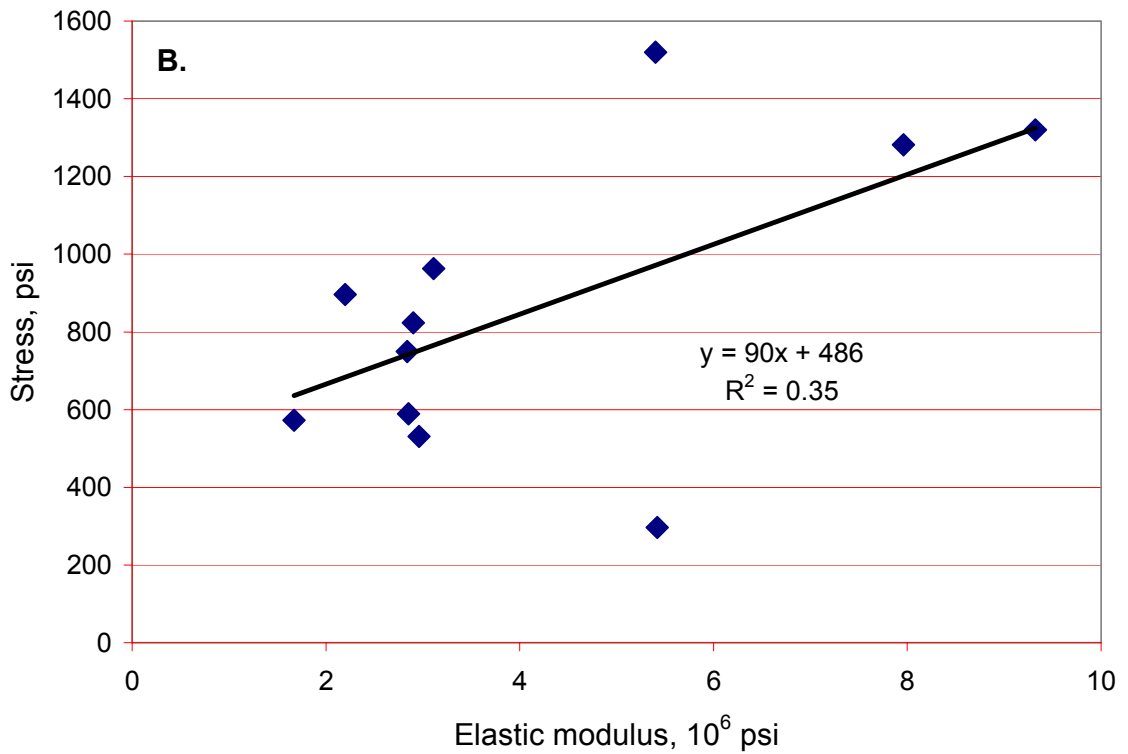
Figure 7-2B. The minimum horizontal stress versus the elastic modulus, eastern Mid-Continent region.
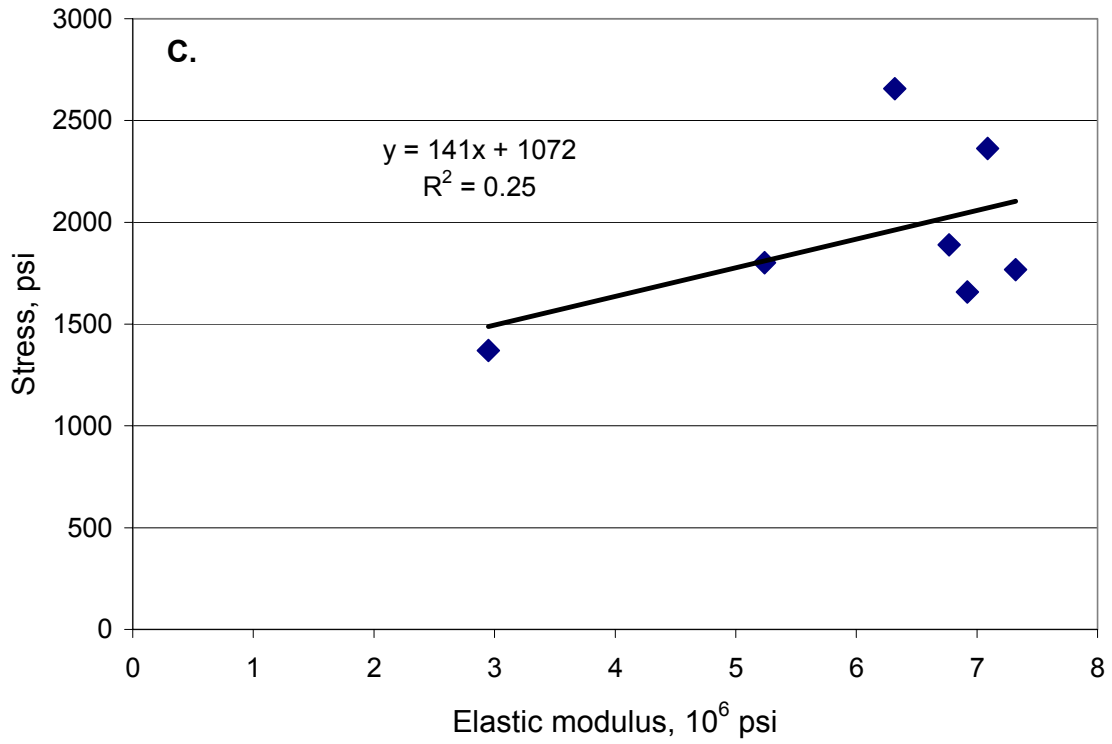
Figure 7-2C. The minimum horizontal stress versus the elastic modulus, central Appalachian region (low strain zone).
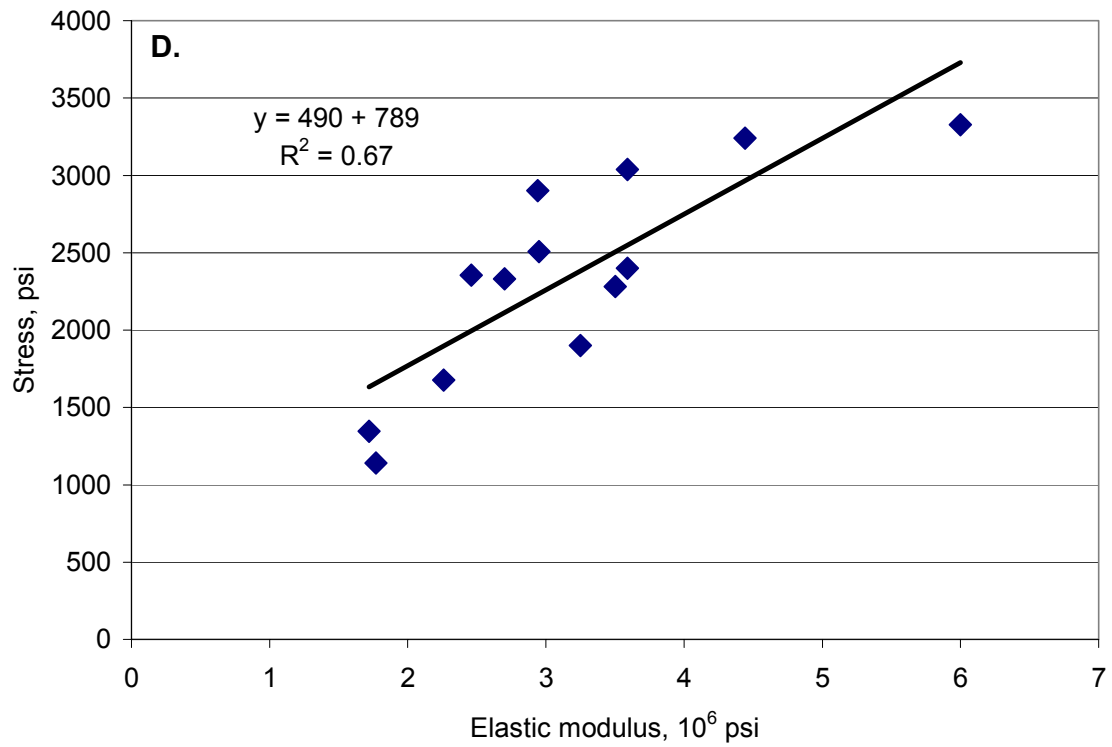
Figure 7-2D. The minimum horizontal stress versus the elastic modulus, central Appalachian region (high strain zone).

Table 7-2 also gives the average ratio between the maximum and minimum horizontal stress for each region. Because of the regional variation of the ratio as indicated by the standard deviations, the minimum stress is not as strongly dependent on the elastic modulus as the maximum horizontal stress. This is especially true for the eastern Mid-Continent region with a standard deviation of the ratio that is about 65 percent of the regional ratio, a ratio that is the highest of any of the regions. Further, the overall lower strains with equal or larger strain variations are another reason why the minimum stress is not as dependent on the elastic modulus.

7.1.2 Variation of Horizontal Stress with Depth

The variation of the horizontal stress with depth is evaluated for each region using the average maximum horizontal stress measured at each site. Site averages are used to give each site the same weight. For the central Appalachian region, the analysis is conducted on the separate data sets for the high and low strain zones as well as for a combined data set. For the regression analysis, equation 3.7 is used. Figure 7-3 shows graphs of the maximum horizontal stress versus depth for each region.

Table 7-3 shows the resulting coefficients, constants and statistics for each region. The depth factor varies from 1.03 to 1.71 psi/ft. However, the correlations are so poor that the depth can only explain between 9 and 24 percent of the variation of the maximum horizontal stress even though the depth range appears to be sufficient. Also, the t statistics for the depth factor indicates that at a 0.05 significance level, none of the depth factors are significantly greater than zero. Essentially, there is no significant increase in the maximum horizontal stress with depth in any of the regions.

Table 7-3. Variation of the maximum horizontal stress with depth by region.

Zone	Number of sites	Depth factor, K_D, psi/ft	Maximum stress at surface, P_S, psi	Coefficient of determination, R^2	t statistic for depth factor	Significant depth factor[1]	Range of depth, ft
Northern Appalachian							
	7	1.03	2784	0.13	0.85	No	400-2,300
Central Appalachian							
Low strain	7	1.71	1527	0.18	1.06	No	550-1130
High strain	13	1.09	2238	0.09	1.02	No	350-1,600
Combined	20	1.26	2018	0.11	1.52	No	350-1,600
Eastern Mid-Continent							
	11	1.07	1186	0.24	1.68	No	290-1,870

[1]Significant at a 0.05 significance level.
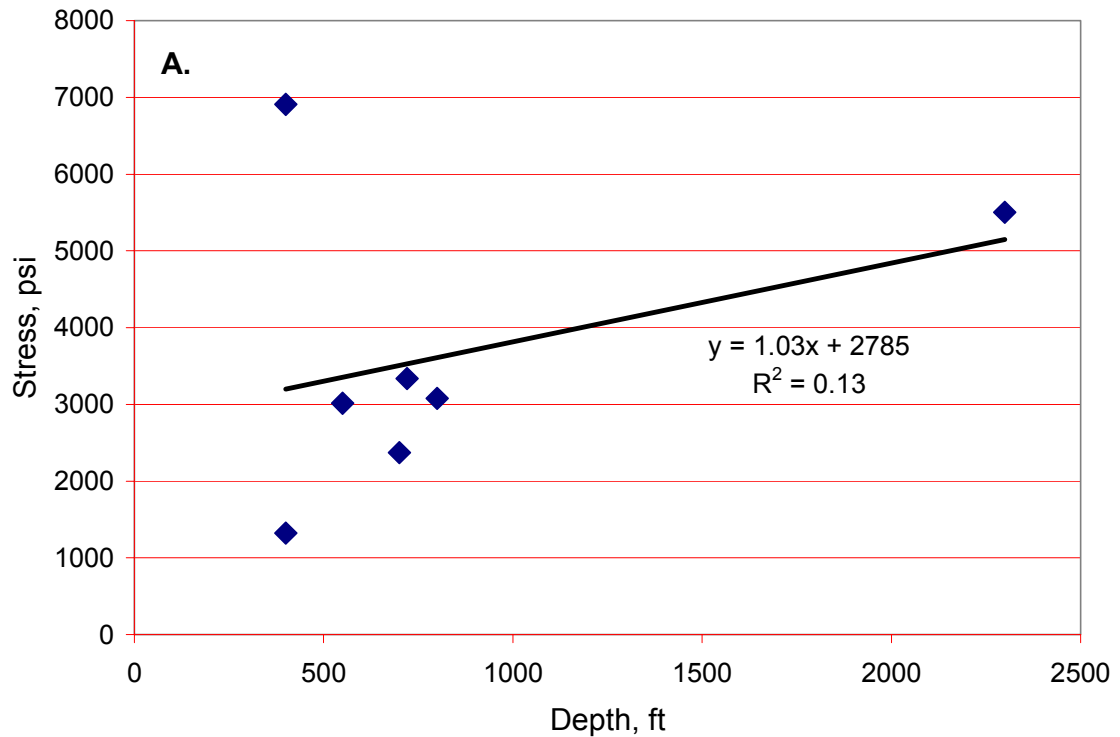
Figure 7-3A. The maximum horizontal stress versus the depth, northern Appalachian region.
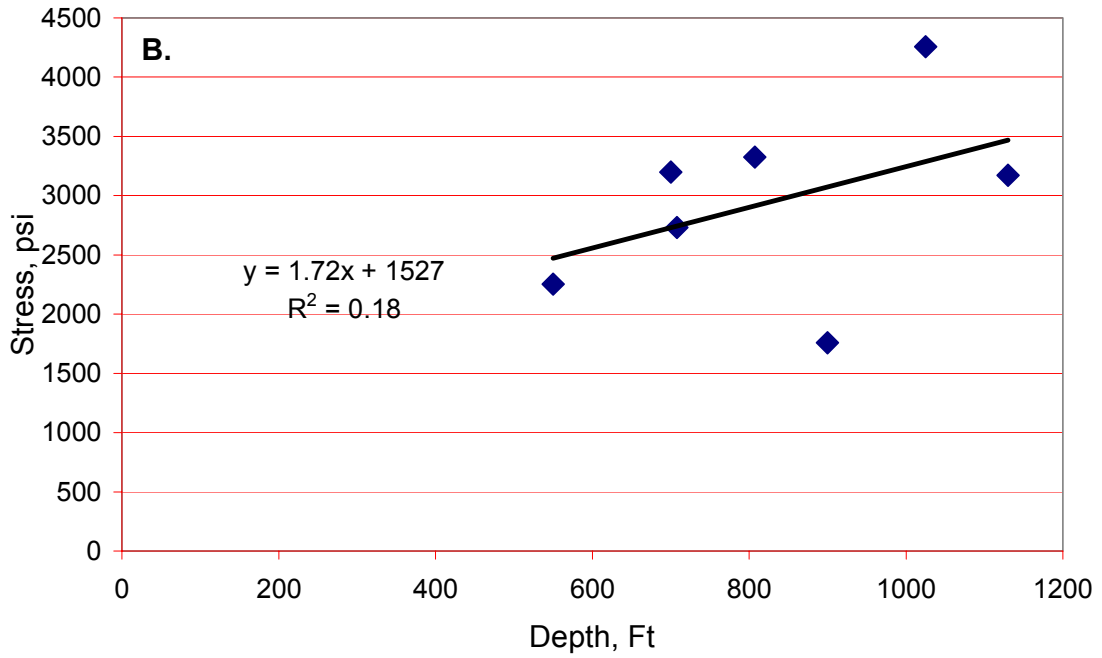
Figure 7-3B. The maximum horizontal stress versus the depth, central Appalachian region (low strain zone).
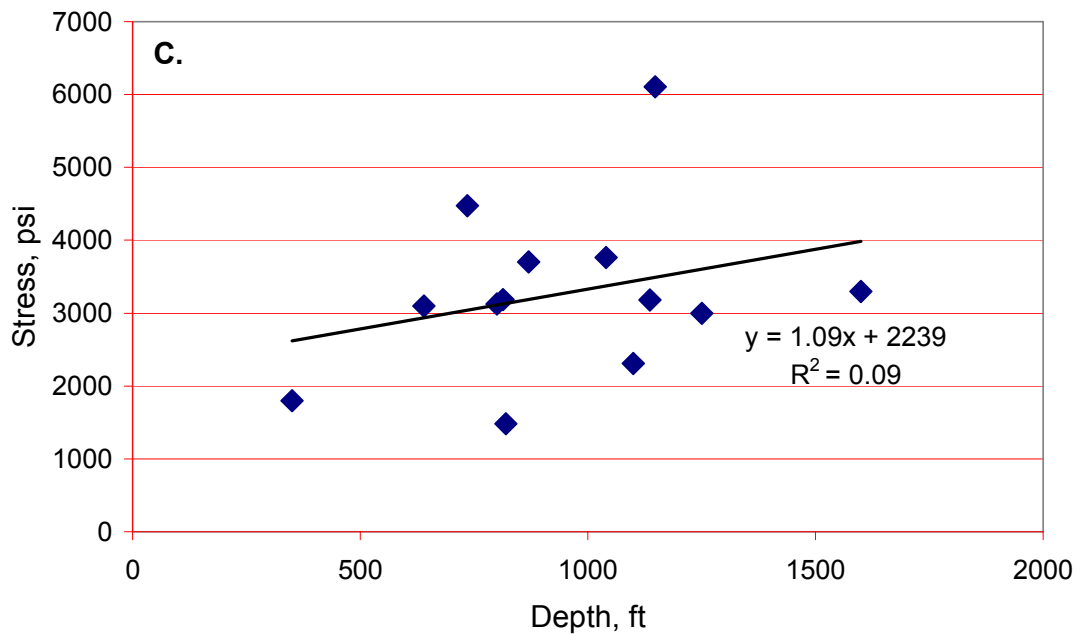
Figure 7-3C. The maximum horizontal stress versus the depth, central Appalachian region (high strain zone).
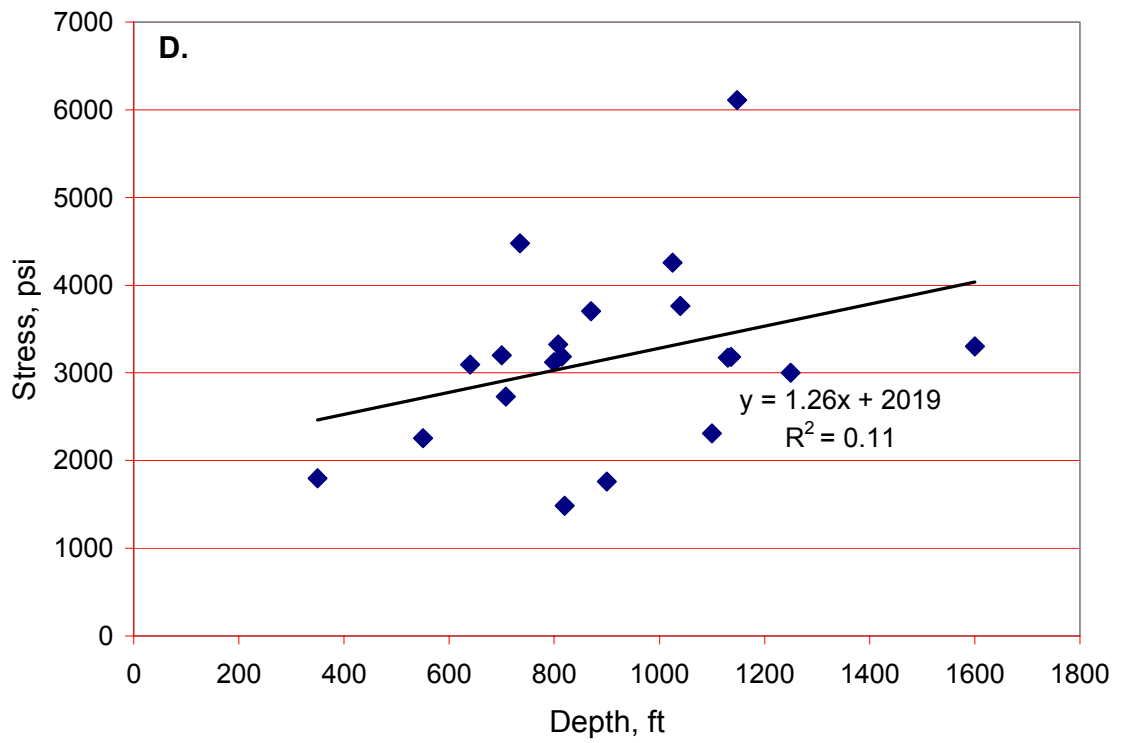
Figure 7-3D. The maximum horizontal stress versus the depth, central Appalachian region.
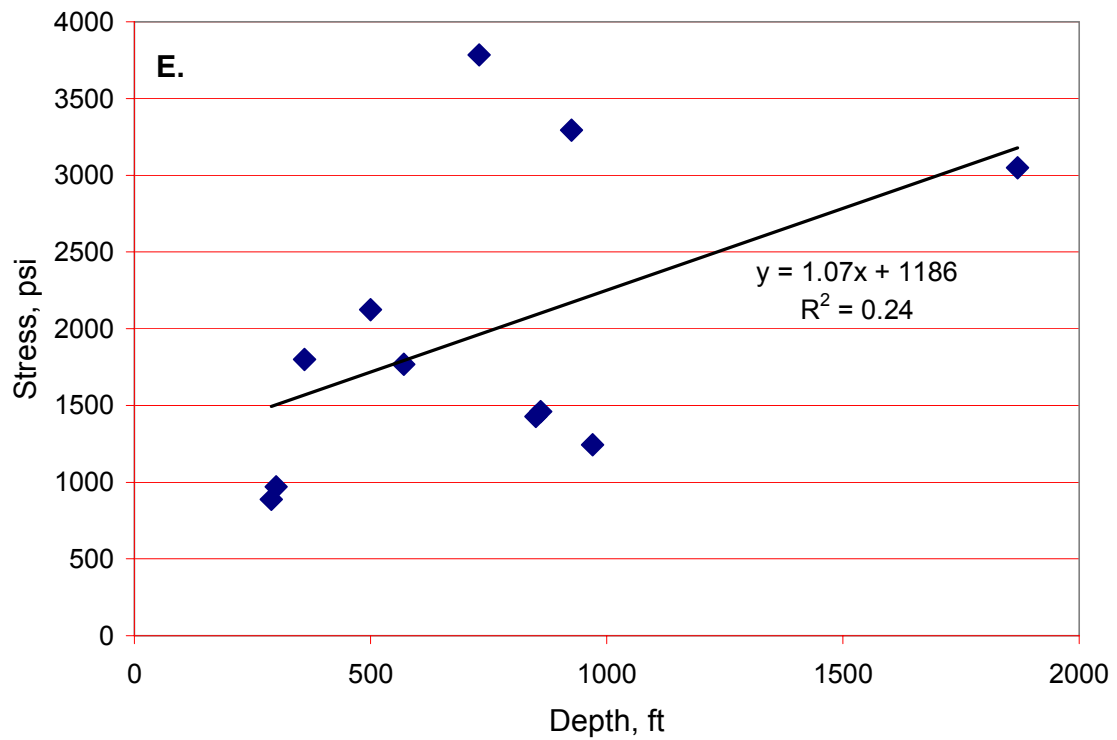
Figure 7-3E. The maximum horizontal stress versus the depth, eastern Mid-Continent region.

7.1.3 Variation of the Horizontal Stress with the Elastic Modulus and Depth

A multiple linear regression model is fit to the data for each region where the dependent variable is the maximum horizontal stress and the independent variables, the site depth and the elastic modulus. For this analysis, the average site stress and elastic modulus are used. The regression analysis is conducted using equation 3.8.

Table 7-4 gives the resulting depth and elastic modulus coefficients, the constants and relevant statistics. In general, the coefficients of determination are fairly high indicating that the models can explain between 83 to 94 percent of the variation of the maximum horizontal stress. For the elastic modulus, the coefficients range from 350 to 1,027 micro strains. In all cases, the coefficient for the elastic modulus is significant at a 0.05 significance level.

Table 7-4. Variation of maximum horizontal stress with depth and the elastic modulus by region.

Zone	Number of measurements	Depth factor, psi/ft	Elastic modulus coefficient, micro strain	Con-stant	Coefficient of determination, R^2	t Statistic for depth factor	Significant depth factor[1]	t statistic for elastic modulus factor	Significant elastic modulus factor[1]
Northern Appalachian									
	7	0.05	560	76	0.89	0.09	No	5.21	Yes
Central Appalachian									
Low strain	7	1.35	424	-752	0.83	1.65	No	3.97	Yes
High strain	13	-0.52	1027	515	0.92	-1.39	No	9.93	Yes
Eastern Mid-Continent									
	11	0.39	350	207	0.94	1.87	No	9.35	Yes

[1]Evaluated at a 0.05 significance level.

The depth factor though is more variable. One of the depth factors is negative, two others are positive while one has a rate of nearly zero. However, none of the depth factors are significantly greater than zero at a 0.05 significance level. This analysis shows that the elastic modulus is a significant factor while the depth is not a significant factor in the variation of the maximum horizontal stress for each region.
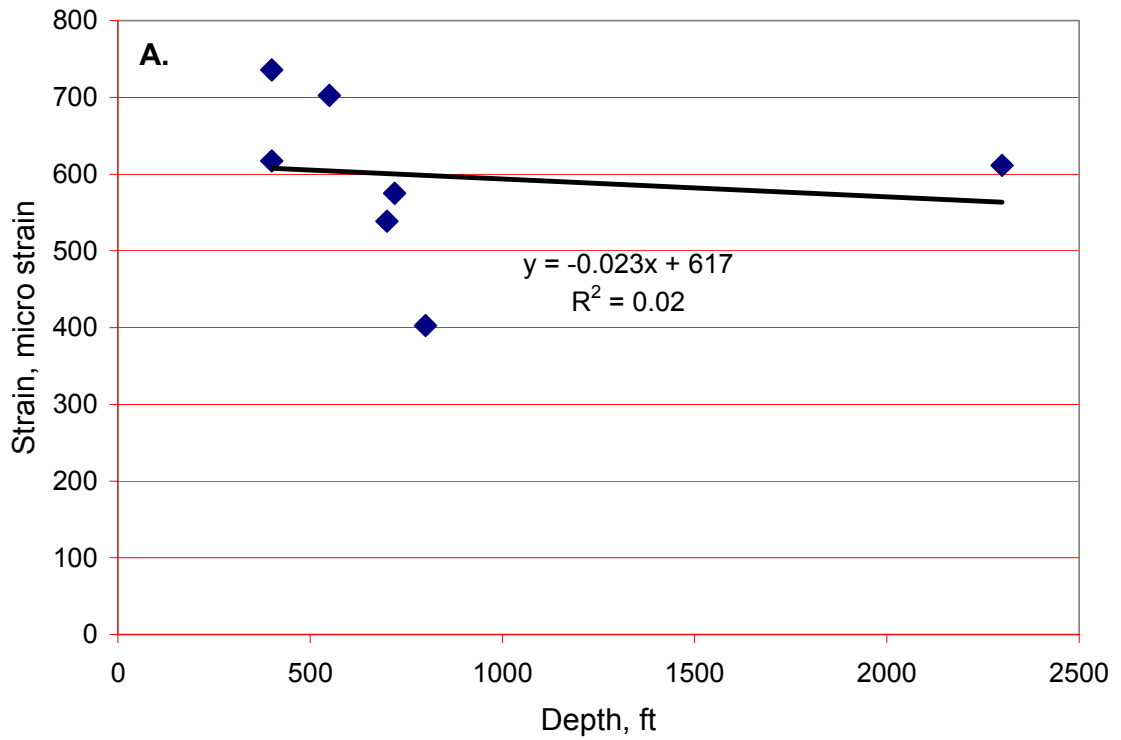
Figure 7-4A. Strain from the maximum horizontal stress versus the depth for the northern Appalachian region.
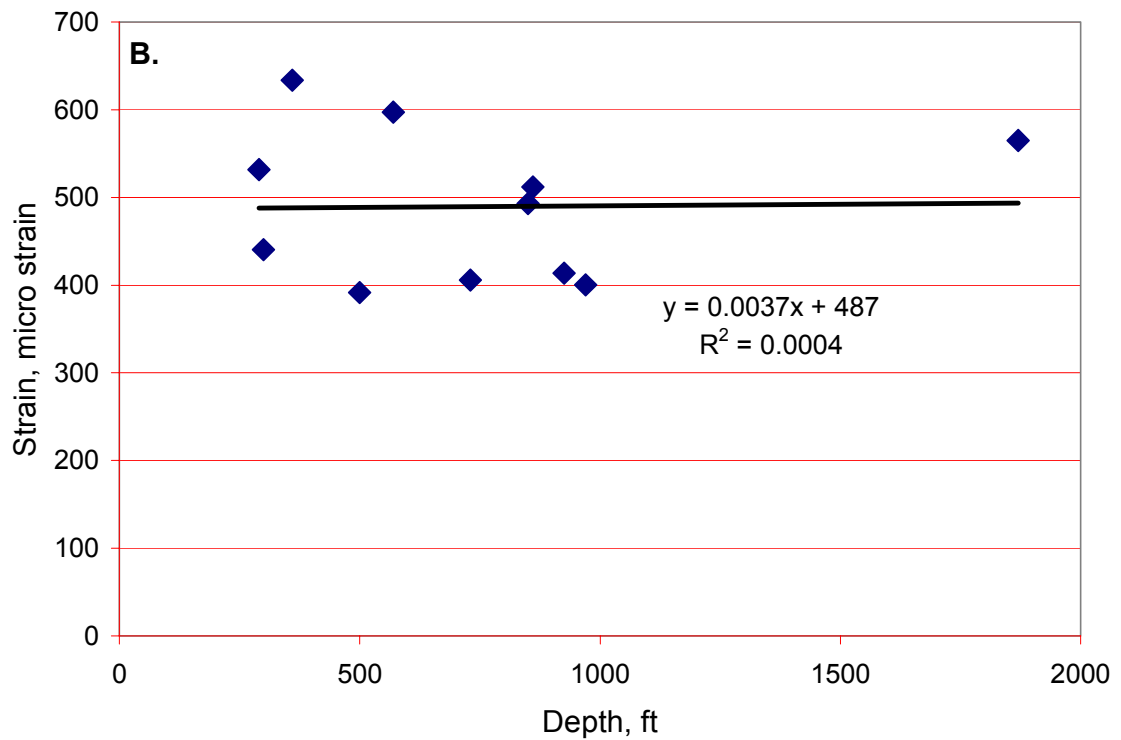
Figure 7-4B. Strain from the maximum horizontal stress versus the depth for the eastern Mid-Continent region.
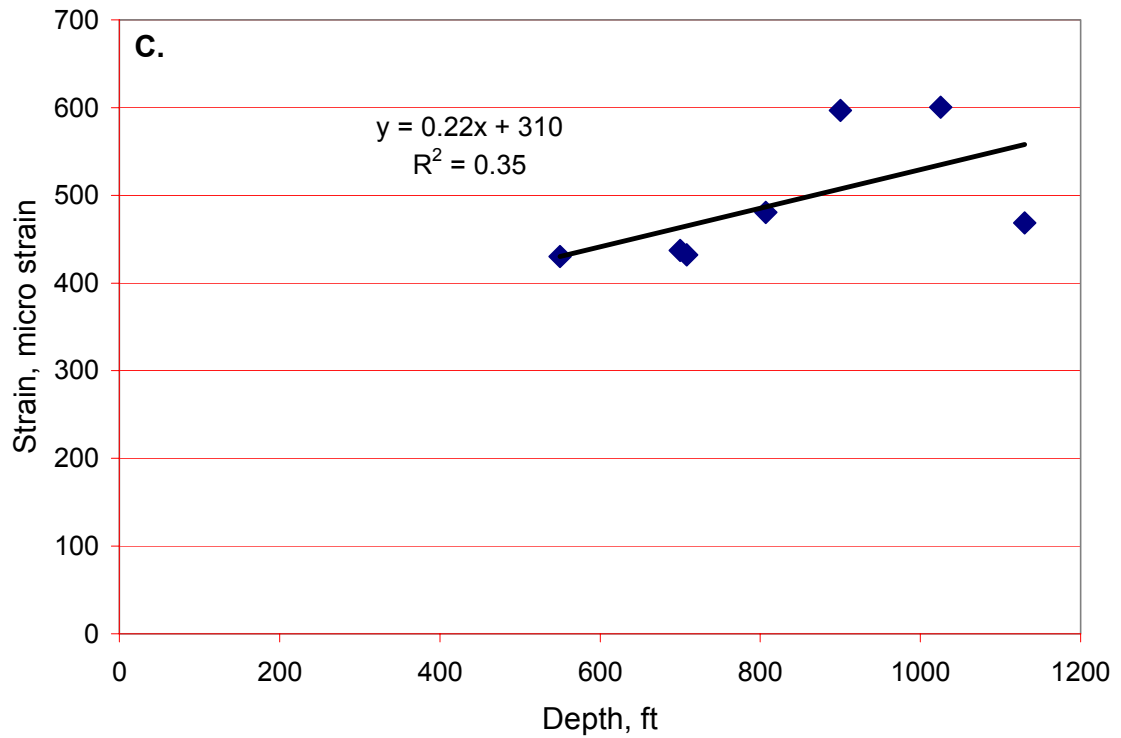
Figure 7-4C. Strain from the maximum horizontal stress versus the depth for the central Appalachian region (low strain zone).
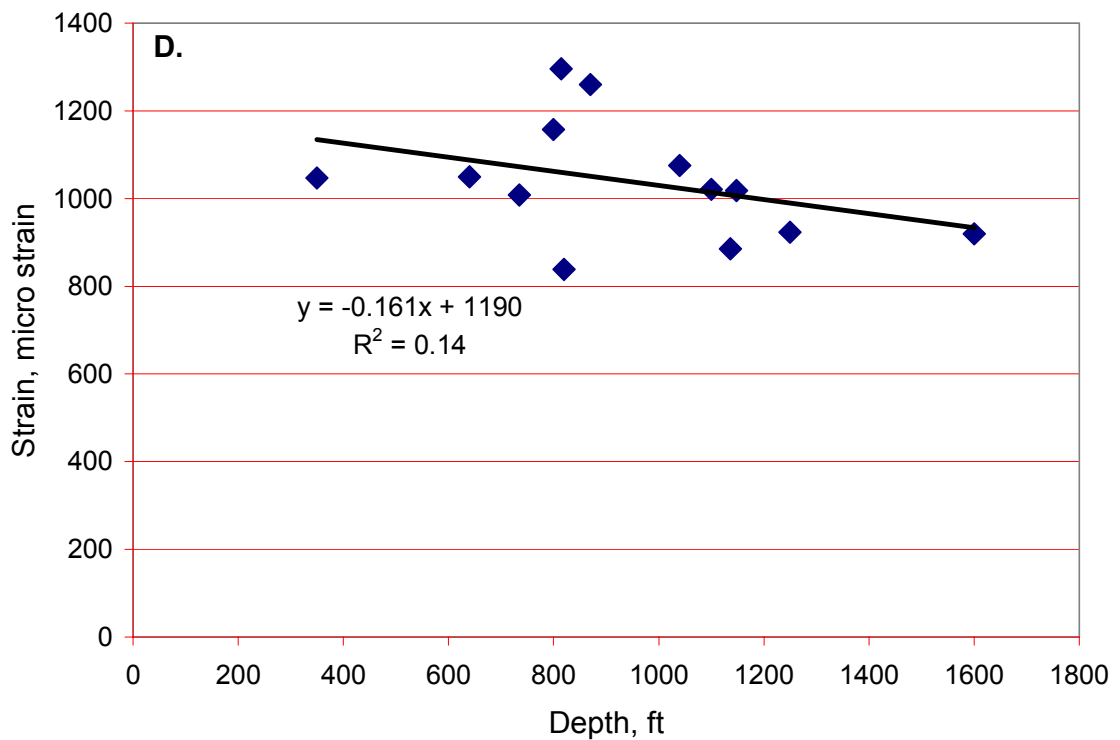
Figure 7-4D. Strain from the maximum horizontal stress versus the depth for the central Appalachian region (high strain zone).

7.1.4 Variation of the Strain from the Maximum Horizontal Stress with Depth

Using the strains from the maximum horizontal stress, the affects of depth are considered without the influence of the elastic properties. These strains are calculated using equation 3.6. The maximum strains calculated by equation 3.6 can also be considered the maximum stress normalized by the elastic modulus. Essentially, the affects of the elastic modulus are removed from the data with all sites and measurements having an elastic modulus of one million psi.

Figure 7-4 shows the strain from the maximum horizontal stress versus depth for each region. A regression analysis using equation 3.9 is used to fit to the data. Table 7-5 gives the depth coefficients, strain constants and relevant statistics from the regression analysis for each region. In general, the coefficients of determination are very low where the depth can explain only between 0 to 35 percent of the variation. For two of the regions, the strain actually decreases with depth. However, none of the regional depth factors are significantly greater than zero at a 0.05 significance level. In general, it does not appear the strains are increasing with depth in any of the regions.

Table 7-5. Regression models for the strain from the maximum horizontal stress versus depth for each region.

Zone	Number of sites	Depth coefficient micro strain/ft	Constant, micro strain	Coefficient of determination, R^2	Significance of strain coefficient
Northern Appalachian					
	7	-0.02	617	0.02	No
Central Appalachian					
Low strain	7	0.22	310	0.35	No
High Strain	13	-0.16	1190	0.14	No
Eastern Mid-Continent					
	11	0.0037	487	0.0004	No

7.1.5 Excess Horizontal Stresses

To calculate the excess horizontal stress, a Poisson's ratio of 0.25 and the average site stresses are used. A linear regression is fit through the data with a zero intercept using equation 3.5. Table 7-6 shows the resulting coefficients and coefficients of

determination for each region. The coefficient of the equation represents the excess or tectonic strain components related to the maximum excess horizontal stress.

Table 7-6. Regression models for the maximum excess horizontal stress versus the elastic modulus by region with a zero intercept.

Site	Number of sites	Coefficient, K_1	Coefficient of determination, R^2
Central Appalachian Region			
Low strain	7	436	0.76
High strain	13	923	0.86
Northern Appalachian Region			
General	7	530	0.87
Eastern Mid-Continent			
General	11	391	0.91

Theoretically, there is a basis for some increase in the horizontal stress with depth, the increase due to gravity from Poisson's effect. However, this effect appears to be masked in the depth models, possibly by the variation in the strain fields. To have a model that includes this depth factor and the elastic modulus requires building a model utilizing the excess horizontal stress. Combining equation 3.5 with the expected increase of the horizontal stress with depth results in the following type of equation

$$P = 1.1 \; [\nu/(1-\nu)] \; D + K_1 \; E. \qquad (7.1)$$

The coefficient of the elastic modulus, K_1, is a strain coefficient. This model can be used to estimate the maximum horizontal stress magnitude within a region.

A similar type of analysis using equation 3.5 is conducted for the minimum excess horizontal stress. Table 7-7 shows the resulting coefficients for the elastic modulus and the coefficients of determination for each region. Except for the northern Appalachian region and possibly the central Appalachian high strain zone, the coefficient of determination is so poor as to make the results of the regression analysis meaningless.

Table 7-7. Regression models for the minimum excess horizontal stress versus the elastic modulus by region with a zero intercept.

Zone	Number of sites	Coefficient, K_1	Coefficient of determination, R^2	Stress ratio max/min	Standard deviation of ratio
Northern Appalachian					
	7	350	0.73	1.38	0.22
Central Appalachian					
Low strain	7	260	0.02	1.67	0.44
High strain	13	610	0.49	1.47	0.24
Eastern Mid-Continent					
	11	123	0.03	4	4.37

For the northern Appalachian region, the coefficient of determination is 0.73. Adding in the depth factor, the equation for the minimum horizontal stress for the northern Appalachian region is

$$Q = 1.1\ [v/(1\text{-}v)]\ D + 350\ E. \tag{7.2}$$

Clearly, the minimum excess horizontal stress variation is not as dependent on the elastic modulus as is the maximum excess horizontal stress variation. Table 7-7 shows the stress ratio and the standard deviations. These ratios are based on the average for all the measurements within the region. The regional average ratios vary from 1.38 to 4.0 and are slightly different than those for the measured stresses because the depth factor is removed from the excess horizontal stresses. However, the standard deviations especially in the eastern Mid-Continent region results in the minimum excess horizontal stress not being as dependent on the elastic modulus as the maximum excess horizontal stress.

7.2 VARIATION OF THE HORIZONTAL STRESSES WITH THE ELASTIC MODULUS FOR SPECIFIC SEAMS AND MINES

In general, the more local the analysis of the horizontal stress and the elastic modulus, the more consistent and uniform the horizontal strain field should be. A more uniform strain field should result in a better correlation between the horizontal stress and

the elastic modulus. However, as is seen in the evaluation of the individual sites and mines in the Beckley seam, the limitation of a more local analysis is a potential lack of a sufficient elastic modulus range. In the Beckley seam, only for the Bonny Mine, is there a sufficient range of the elastic properties and uniform strain field to result in a strong correlation. Therefore, only the analysis from those locations that have a sufficient range in the elastic modulus are presented in this section. Further, the individual stress measurements are used in this section and not the site averages.

7.2.1 Pittsburgh Seam

Figure 7-5 shows a graph of the maximum horizontal stress versus the elastic modulus for the three sites in the Pittsburgh seam. A linear regression fit through the data results in the following equation

$$P = 370\ E + 728. \tag{7.3}$$

The coefficient of determination is 0.87 and represents a fairly strong correlation between the elastic modulus and the maximum horizontal stress.
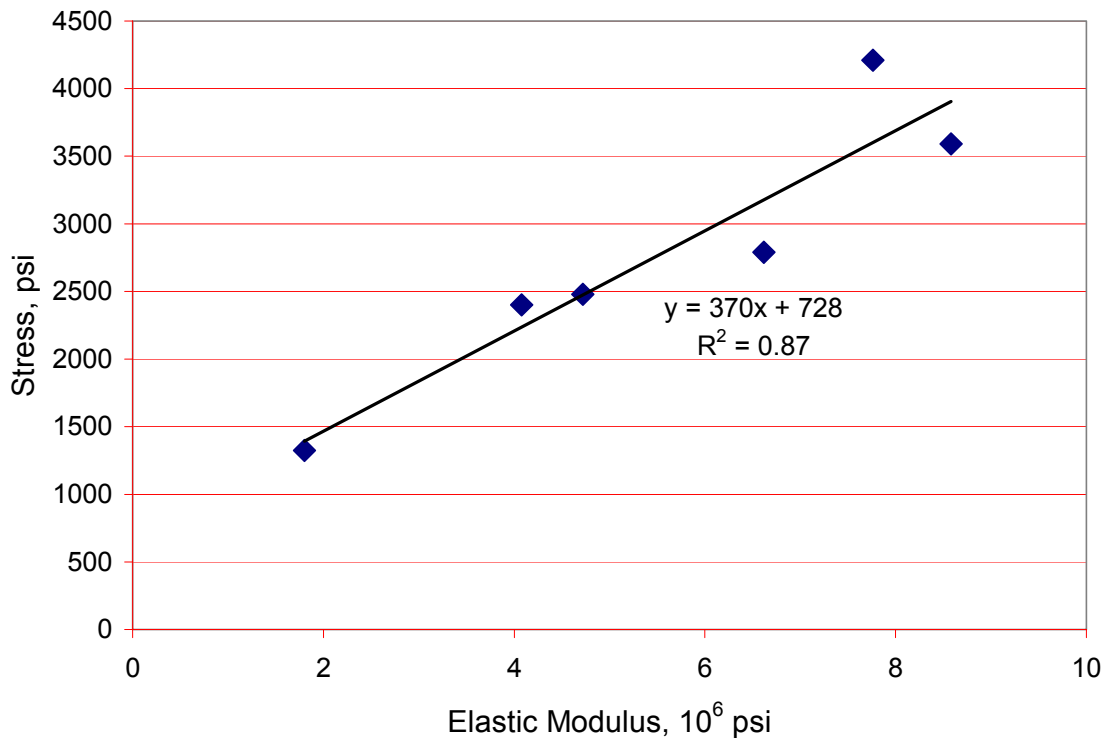
Figure 7-5. The maximum horizontal stress versus the elastic modulus for the Pittsburgh seam.

For the 3 sites in the Pittsburgh seam, the elastic modulus ranges from 1.8 to 8.58 million psi. The average site strains from the maximum horizontal stress are for site 1, 461 micro strains, site 2, 557 micro strains and site 3, 736 micro strains. However, even with some difference in the strain fields, there is still a strong correlation between the elastic modulus and the horizontal stress because of the large difference in the elastic modulus between the sites.

The elastic modulus versus the maximum excess horizontal stress can also be examined. A linear regression fit through the data with a zero intercept results in the following equation

$$P_e = 440 \ E. \hspace{4cm} (7.4)$$

The coefficient of determination is 0.79. The coefficient for the elastic modulus results in an excess strain from the maximum horizontal stress for the Pittsburgh seam of 440 micro strains.

For the minimum horizontal stress, the resulting regression equation is

$$Q = 171 \ E + 1122. \hspace{3.5cm} (7.5)$$

The coefficient of determination is 0.65. The correlation is weaker than for the maximum horizontal stress but still fairly strong.

7.2.2 Lower Kittanning Seam

From the West Virginia site data, Aggson (1985) noted a relationship between the maximum horizontal stress and the elastic modulus. A linear regression fit through all the data produced the relationship

$$P = 600 \ E - 69. \hspace{3.8cm} (7.6)$$

The resulting coefficient of determination was 0.83.

Figure 7-6 shows a graph of the elastic modulus versus the maximum horizontal stress for both mines. In the present analysis, only those measurements beyond 15 feet in depth are used from the West Virginia site. A linear regression is fit through the data with the resulting equation

$$P = 665\,E + 57. \tag{7.7}$$

The coefficient of determination is 0.95. There is a very strong correlation between the elastic modulus and the maximum horizontal stress. Further, the equation is very similar to the equation developed by Aggson (1985). For both mines, the range in the elastic modulus is from 1.6 to 6.95 million psi. The average site strain from the maximum horizontal stress is for the Tanoma Mine, 575 micro strains and for the Philippi, WV mine, 721 micro strains. A strong correlation is still developed even with some difference in the strain fields.
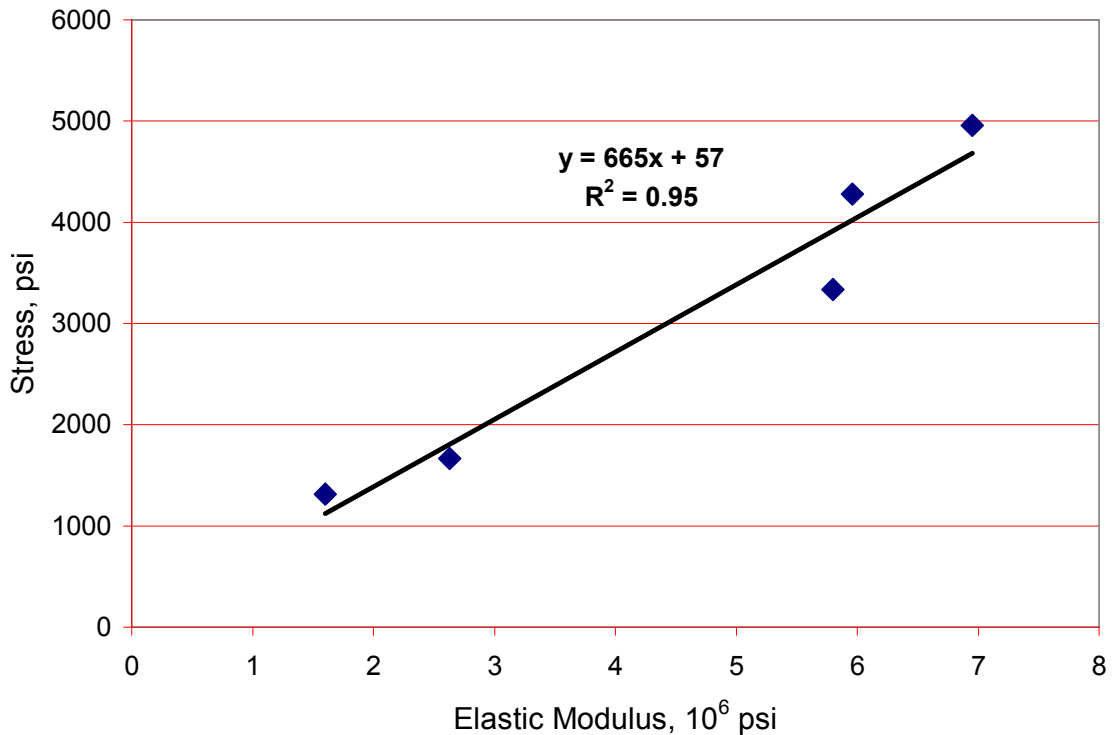
Figure 7-6. The maximum horizontal stress versus the elastic modulus for the lower Kittanning seam.

The relationship between the elastic modulus and the maximum excess horizontal stress is also developed. For the maximum excess horizontal stress with the regression forced through zero, the equation is

$$P_e = 637 \ E. \qquad\qquad (7.8)$$

The coefficient of determination is 0.95. Essentially, the strain from the maximum excess horizontal stress in the lower Kittanning seam is 637 micro strains.

For the minimum horizontal stress versus the elastic modulus, the following equation is developed

$$Q = 497 \ E. \qquad\qquad (7.9)$$

The coefficient of determination is 0.96. This is a very high correlation especially for the minimum horizontal stress.

The relationship between the minimum excess horizontal stress and the elastic modulus is

$$Q_e = 462 \ E. \qquad\qquad (7.10)$$

This implies the strain from the minimum excess horizontal stress is 462 micro strains.

7.2.3 Peabody #10 Mine, Eastern Mid-Continent Region

For the Peabody #10 Mine, a strong relationship between the horizontal stress and the elastic modulus has been noted previously (Hanna et al., 1991). The range in the elastic modulus from 1.28 to 5.7 million psi appears to be sufficient to establish an adequate relationship between the elastic modulus and the maximum horizontal stress. Figure 7-7 shows a graph of the elastic modulus versus the maximum horizontal stress from the mine. In this analysis, only the three deepest measurements are used. The resulting regression equation is

$$P = 608 \, E. \tag{7.11}$$

The coefficient of determination is 0.97. However, there is little or no relationship between the minimum horizontal stress and the elastic modulus at the mine.
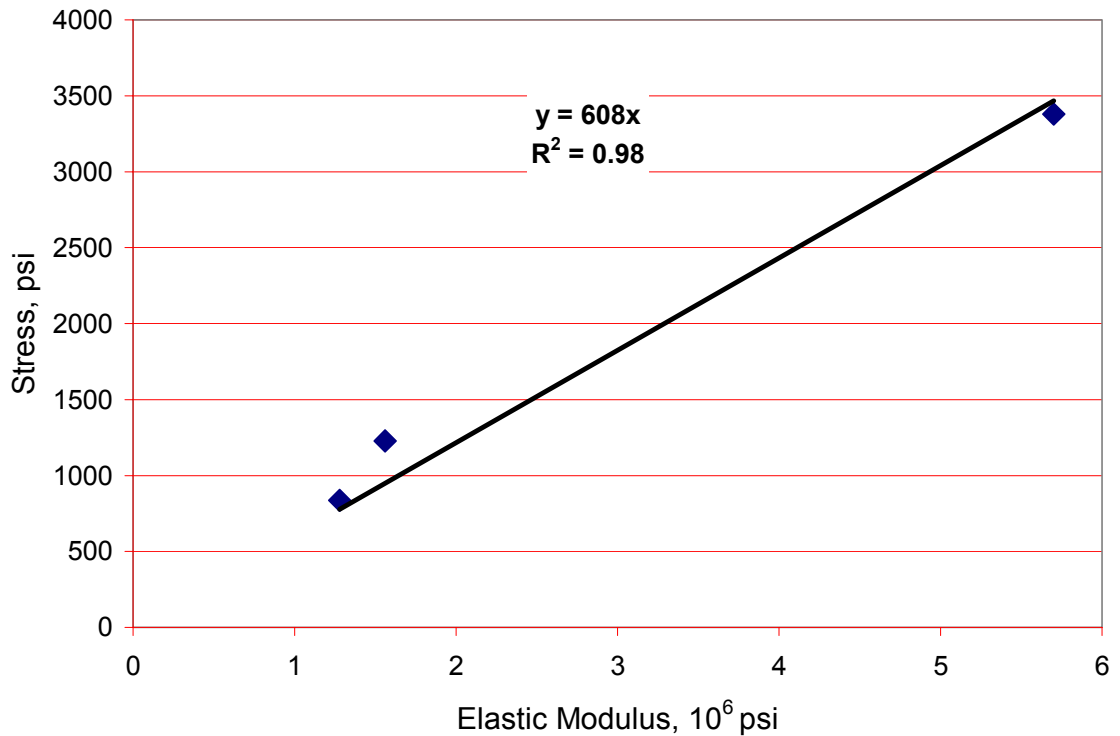
Figure 7-7. The maximum horizontal stress versus the elastic modulus for the Peabody #10 Mine.

7.3 REGIONAL AND LOCAL MODELS-CONCLUSIONS

Regional models can explain a high percent of the variation of the maximum horizontal stress with the elastic modulus. The coefficients of determination for these models range from 0.72 to 0.91.

Regional models indicate that the minimum horizontal stress variation is less dependent on the elastic modulus than the variation of the maximum horizontal stress. This is especially true in the eastern Mid-Continent region and results from the very low minimum applied horizontal strains and the high standard deviation of those strains relative to the average.

None of the regional depth factors are significant. Further, in the models, depth can only explain between 9 and 24 percent of the variation of the maximum horizontal stress. The maximum horizontal stress normalized by the elastic modulus does not increase with depth. Essentially, the elastic modulus can be used to explain the variation that might be attributed to depth, suggesting that the depth is not a significant independent factor.

Regression models for individual mines or groups of sites were developed with the elastic modulus explaining a high degree of the maximum horizontal stress variation. However, a sufficient range of the elastic modulus is usually required to develop adequate models.

CHAPTER 8. HORIZONTAL STRESS AND DEPTH MODELS FOR THE EASTERN UNITED STATES

An examination is made of the variation of the horizontal stress with respect to the elastic modulus and the depth for the eastern United States.

8.1 VARIATION OF THE HORIZONTAL STRESS WITH THE ELASTIC MODULUS

For the elastic modulus, a separate analysis is conducted for both the low and high strain sites. The high strain sites are all from the central Appalachian region and include the sites with an intermediate strain level. Therefore, the high strain model is restricted to the central Appalachian region. However, the low strain model is in general applicable for much of the eastern United States except the intermediate and high strain zones of the central Appalachian region. To eliminate the effects of depth the excess horizontal stresses are used.

Table 8-1. Coefficients and statistics for the maximum and minimum excess horizontal stress models for the eastern United States with a zero intercept.

Region	Number of sites/ measurements	Maximum stress		Minimum stress	
		Coefficient K_P	Correlation coefficient squared	Coefficient K_Q	Correlation coefficient squared
Low Strain Model-Individual Site Measurements					
Northern Appalachian/ Central Appalachian/ Eastern Mid-Continent	67	430	0.71	212	0.24
Low Strain Models-Average Site Stresses and Elastic Modulus					
Northern Appalachian/ Central Appalachian/ Eastern Mid-Continent	25	459	0.83	255	0.47
Eastern Mid-Continent/ Central Appalachian	18	414	0.88	193	0.32
Northern Appalachian	7	530	0.87	350	0.73
High Strain Model-Individual Measurements					
Central Appalachian	48	967	0.66	623	0.1
High Strain Model-Average Site Stresses and Elastic Modulus					
Central Appalachian	13	923	0.86	610	0.49

To examine the variation of the maximum and minimum excess horizontal stress with the elastic modulus, equation 3.5 is fit through the data with a zero intercept. Table 8-1 shows the coefficients for the elastic modulus and the coefficients of determination for low and high strain models for both the maximum and minimum excess horizontal stress. For several of the models, the site average stress and elastic modulus are used though for comparison, models are also given based on the individual measurements. Further, several low strain models are given based on different regional combinations. Again, the main reason for developing separate regional models for the low strain group is the higher strains seen in the northern Appalachian region.

Figure 8-1 shows the maximum excess horizontal stress versus the elastic modulus when the individual measurements are used in the analysis. Regression lines are given separately for the high strain sites and for the low strain sites. There are clearly two groups of data with little overlap between the low and high strain groups. The elastic modulus can explain 71 percent of the variation of the maximum excess horizontal stress in the low strain model and 66 percent of the variation of the maximum excess horizontal stress in the high strain model.
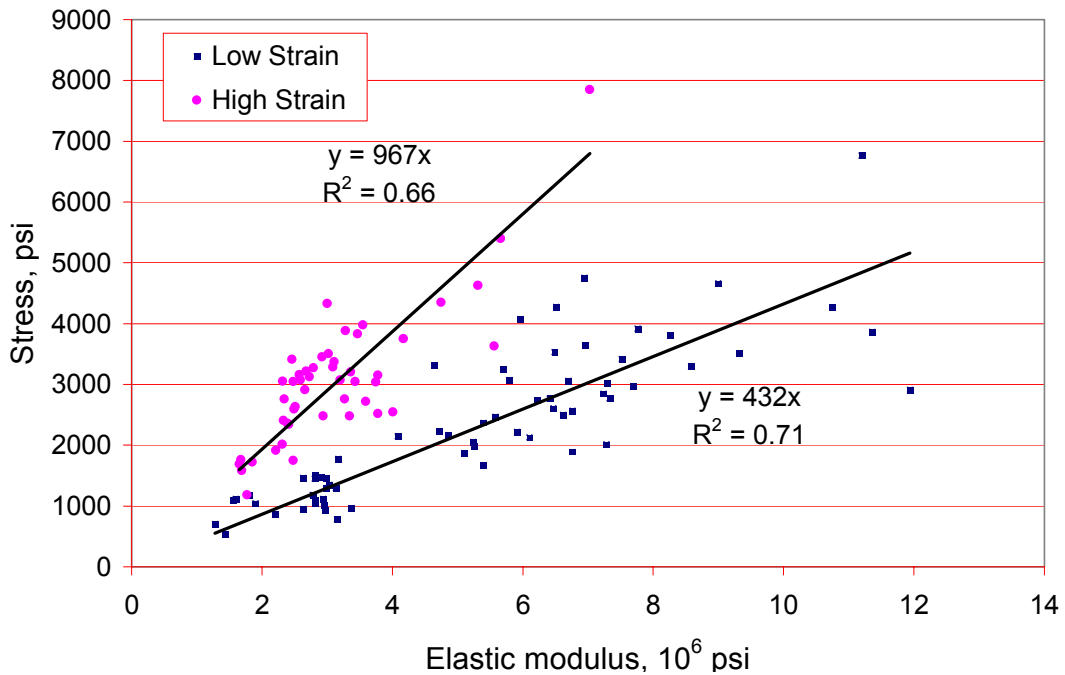
Figure 8-1. The maximum excess horizontal stress versus the elastic modulus for the eastern United States.

Figure 8-2 shows the maximum excess horizontal stress versus the elastic modulus using the site average stresses and elastic modulus. Again, only two regression models are developed one for each strain group. With this data, the elastic modulus explains in the low strain model, 83 percent of the maximum excess horizontal stress variation and in the high strain model, 86 percent of the maximum excess horizontal stress variation. A higher coefficient of determination is achieved with site average stresses than when individual measurements are used. This results from the elimination of the local variations between the individual measurements.
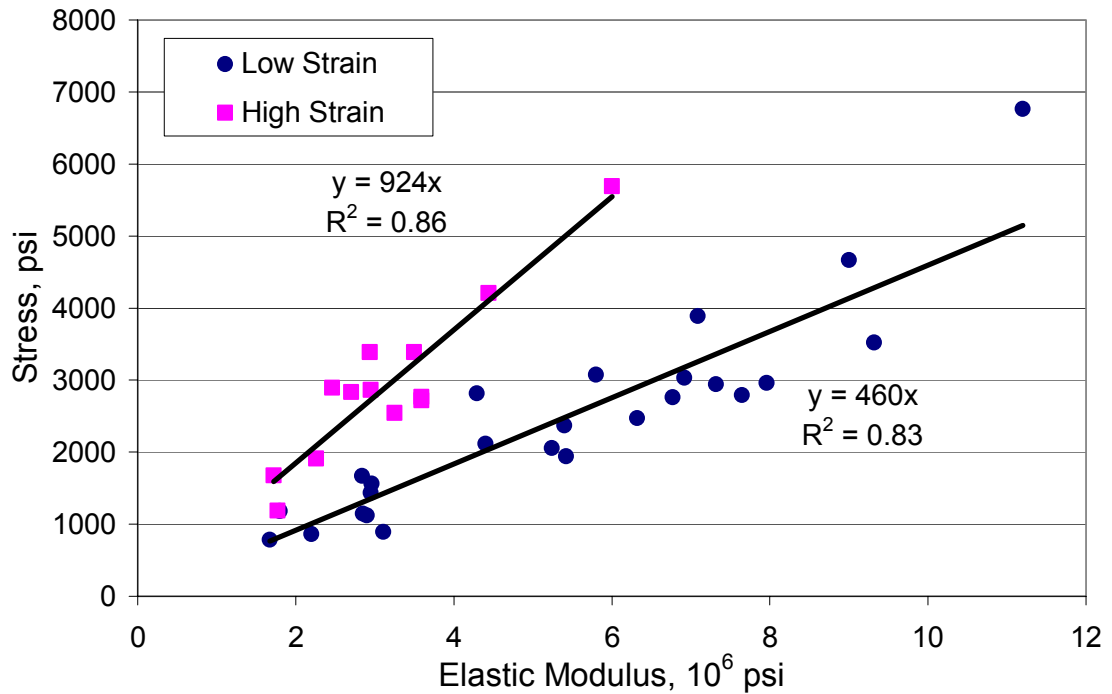
Figure 8-2. The maximum average excess horizontal stress versus the site average elastic modulus for the eastern United States.

Because the northern Appalachian region has strains that are about 20 percent higher than those of the other regions in the low strain group, the low strain group can be further separated into two groups. Again, using the site average stresses, figure 8-3 shows a graph of the maximum excess horizontal stress versus the elastic modulus with the low strain data separated into two groups. The elastic modulus now explains 88 percent of the maximum excess horizontal stress variation in the low strain zone

without the northern Appalachian region and 87 percent of the variation in the northern Appalachian region.
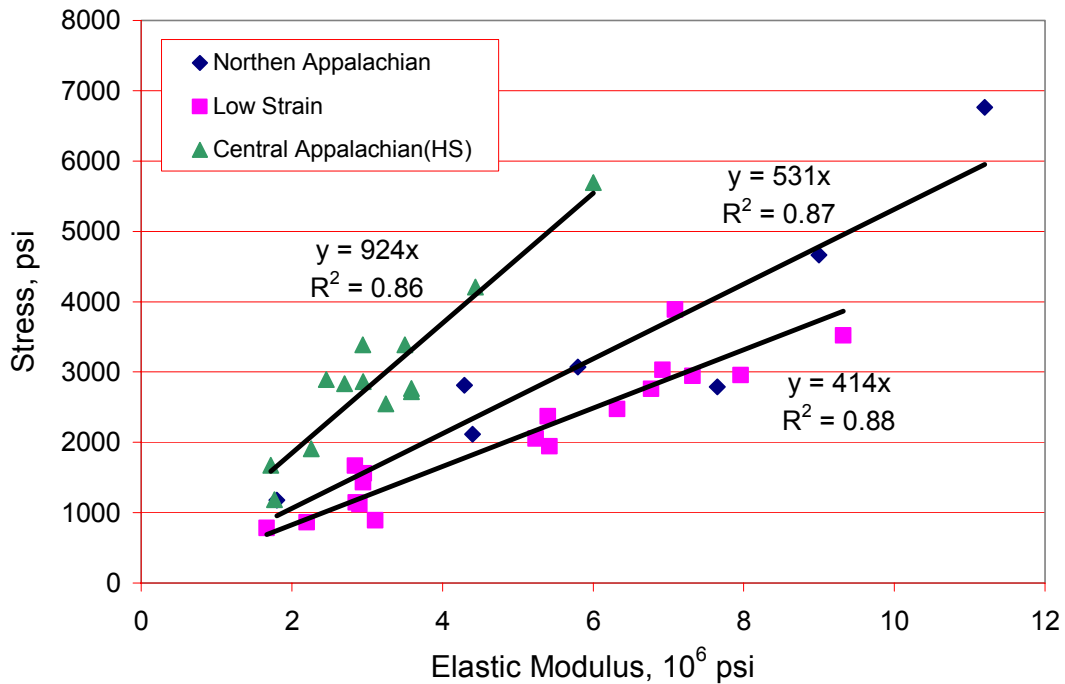
Figure 8-3. The maximum average excess horizontal stress versus the site average elastic modulus for the eastern United States (two low strain models).

These models for the maximum excess horizontal stress can be used to estimate the maximum horizontal stress. The maximum horizontal stress can be calculated for the eastern United States by adding the gravity affects from Poisson's ratio to the equations. In general, a single model for the low and high strain zones can explain a high percent of the variation in the maximum horizontal stress with the elastic modulus. Therefore, the low strain model can be used to estimate the maximum horizontal stress across much of the eastern United States for the site depth range of the data set. However, the low strain zone can be further divided into a combined eastern Mid-Continent and low strain central Appalachian regions and a northern Appalachian region with the two models explaining and even higher percent of the maximum horizontal stress variation with the elastic modulus. The high strain model encompasses the intermediate and high strain zones of the central Appalachian region. However, there are no definitive boundaries over where the model should be applied. In general, the low strain model reflects the strain field

applied across most of the eastern United States including a portion of the central Appalachian region while the high strain model reflects a high strain region that has only been observed in the central Appalachian region.

Table 8-1 also shows the models for the minimum excess horizontal stress. In general, the coefficients of determination are much lower than for the maximum excess horizontal stress. For most of the models, the coefficients of determination are low enough as to make the models unreliable for estimating the minimum excess horizontal stress. Essentially, the minimum excess horizontal stress variation is not as dependent on the elastic modulus. The exception is the northern Appalachian region.

8.2 MAXIMUM HORIZONTAL STRESS VERSUS DEPTH

The change in the maximum horizontal stress with depth across the eastern United States is evaluated based on the average maximum horizontal stress from each site. The site average stresses are used to give each site the same weight. Figure 8-4 shows the depth versus the maximum horizontal stress across the eastern United States. The resulting regression equation is

$$P = 1.27\,D + 1836. \tag{8.1}$$

The coefficient of determination is only 0.15 while the t statistic for the depth coefficient is 2.53. At a 0.05 significance level, the depth factor is significantly greater than zero. Therefore, in general there appears to be a significant increase of about 1.27 psi/ft of depth in the eastern United States though the depth can only explain about 15 percent of the variation. Further, the site in the Columbus limestone in Ohio has a strong influence on the regression analysis and the depth factor because of the large depth (2,300 ft) and high maximum horizontal stress (though not high strain). Also, the depth cannot to a large extent explain the maximum horizontal stresses above 5,000 psi at two other sites with one of the sites having the highest maximum horizontal stress of 6,910 psi in the data set at a depth of only 400 ft. All three of these sites have a relatively high elastic modulus ranging from 6 to 11.2 million psi. These high stresses can be explained by the elastic modulus in combination with the strain field.
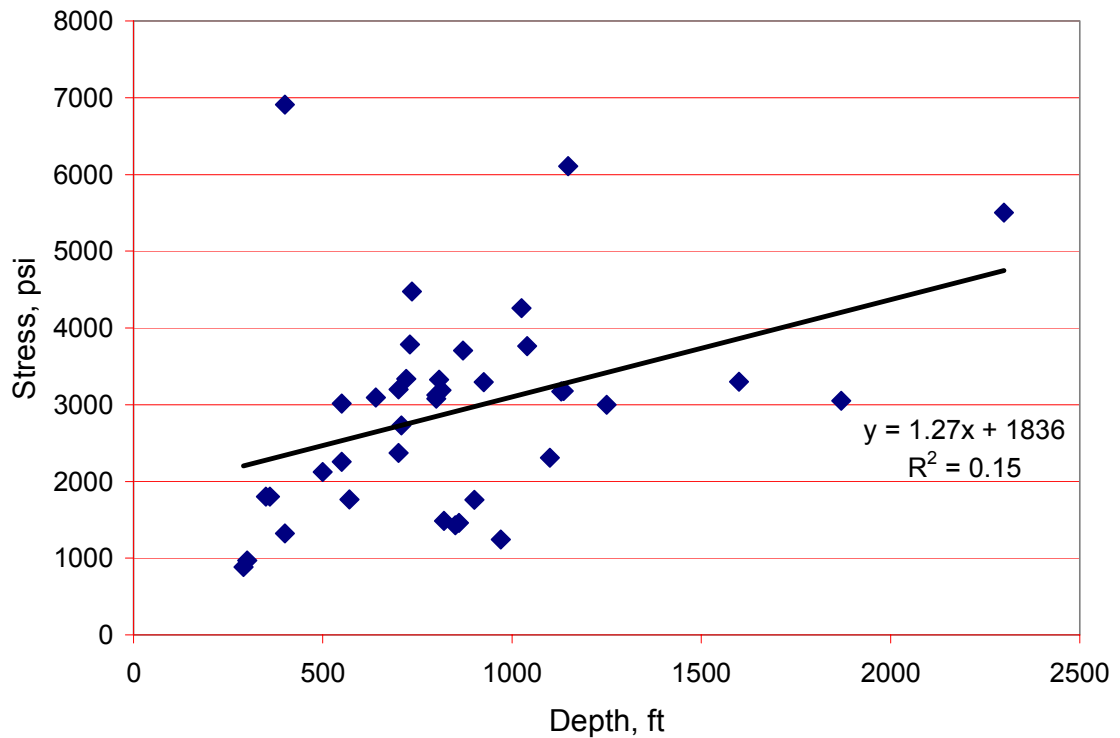
Figure 8-4. The maximum horizontal stress versus the depth in the eastern United States.

Because there was no significant increase with depth in the regional models this significant increase for the eastern United States may be due to the differences in certain parameters between regions. Table 8-2 shows the various average parameters for each region including the depth, elastic modulus and strain. The Illinois basin that includes 7 sites is shown separately from the eastern Mid-Continent region. There are differences in the average depth, elastic modulus and maximum average strain for each region. Although the average strain in the Illinois basin is similar to the other areas, except for the high strain zone, the elastic modulus is much lower and results in a much lower maximum horizontal stress. Combine these lower stresses with the lowest regional average depth and some increase in the horizontal stress will probably be observed in this data set for the eastern United States.

Table 8-2. Summary of average parameters including the depth, maximum horizontal strain and elastic modulus for each region.

Zone	Number of sites	Depth, ft	Elastic modulus, 10^6 psi	Maximum strain, micro strain
Northern Appalachian				
	7	839	6.31	597
Central Appalachian				
Low strain	7	831	6.09	492
High strain	13	946	3.17	1038
Eastern Mid-Continent Region				
	11	747	4.24	489
Illinois Basin				
	7	600	2.65	515

To eliminate the effects of the elastic properties, the relationship between the strain from the maximum horizontal stress and the depth is examined. Figure 8-5 shows the strain from the maximum horizontal stress versus the depth for the eastern United States. The resulting regression equation is

$$\varepsilon_p = 0.08\ D + 632. \tag{8.2}$$

The coefficient of determination is only 0.014 while the t statistic of 1.01 indicates that the depth coefficient is not significantly greater than zero at a 0.05 significance level. The strain data is the maximum horizontal stress normalized by the elastic modulus where all sites have an elastic modulus of one million.

Once the effects of the elastic properties are removed, there is no significant increase in stress with the depth. Further, this depth model can only explain one percent of the variation in the strain or stress. This would suggest that there is some relationship between the depth and the elastic modulus. The correlation between the depth and elastic modulus is 0.24. Although this correlation is weak, it is also positive. Because, the relationship between depth and the maximum horizontal stress is also weak, this low degree of correlation is sufficient to cause the normalized stresses not to be significantly influenced by depth.
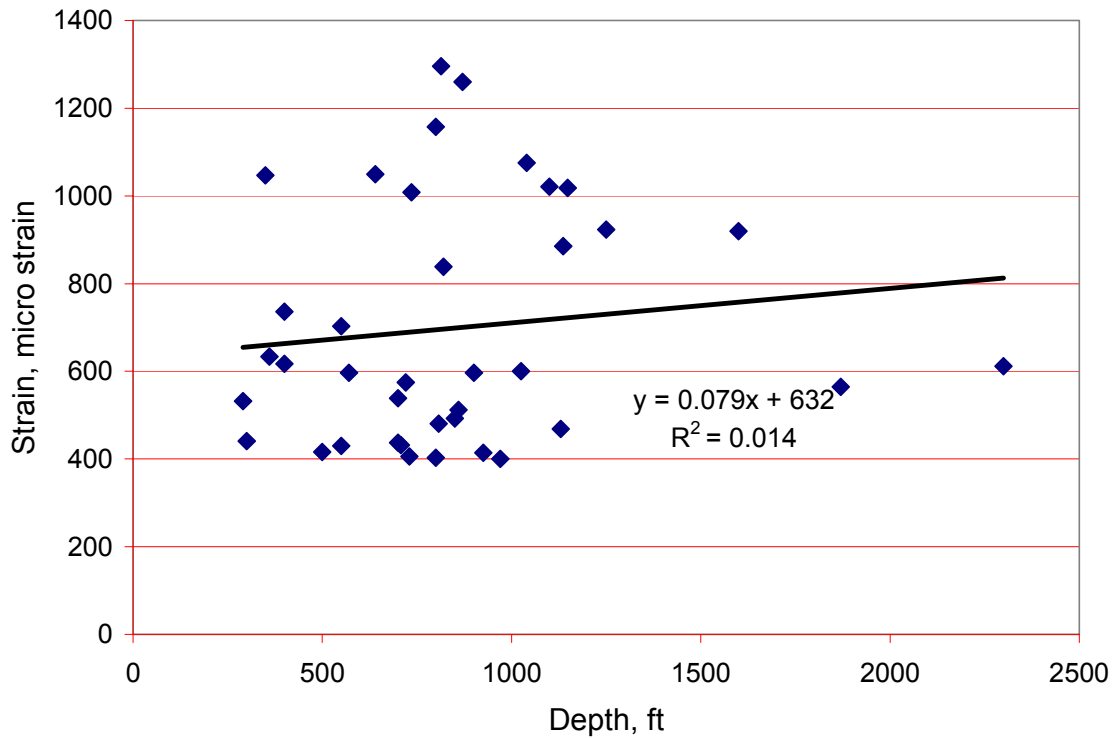
Figure 8-5. The strain from the maximum horizontal stress versus the depth for the eastern United States.

Because the stress-elastic modulus models depend on, and are developed from, a sufficiently uniform strain field, the regional differences in depth and strain are considered. If only the twenty-five low strain sites are used, then the resulting equation is

$$\varepsilon_p = 0.007\, D + 515. \tag{8.3}$$

The coefficient of determination is only 0.0009 while the t statistic of 0.14 indicates that the depth coefficient is not significantly greater than zero at a 0.05 significance level. In the low strain regions there is no increase in the strain with depth.

Because the depth is not causing a significant increase in the strain in this data set, the depth cannot be used in general as an independent variable in developing the models that include the elastic modulus. Essentially, the elastic modulus can explain the increase and variation of the maximum horizontal stress. If the strains did increase with depth, then models must be developed with the strains and therefore the variation of the stress with the

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elastic modulus also dependent on the depth. In such a case, the strain or the affects of the elastic modulus would not be independent of the depth.

However, there is no significant increase in the horizontal strain with depth. The apparent significant increase of the horizontal stress with depth across the eastern United States appears to be due to the regional differences in the elastic modulus, strain and depth. Essentially, the range of depth may be too limited and the stresses obtained over too wide of a geographic area to be used to establish a depth factor for the stress or strain across the eastern United States.

8.3 HORIZONTAL STRESS AND DEPTH MODELS FOR THE EASTERN UNITED STATES-CONCLUSIONS

A high and low strain model developed for the eastern United States can explain 83 and 86 percent of the variation of the maximum excess horizontal stress with the elastic modulus. This implies that large areas of the eastern United States are subjected to a sufficiently uniform strain field from the maximum horizontal stress to allow for such strong correlations.

In general, the models for the minimum horizontal stress and elastic modulus have a much lower coefficient of determination than for the maximum excess horizontal stress. Essentially, the minimum horizontal stress variation is not as dependent on the elastic modulus.

Depth does cause a significant increase in the maximum horizontal stress across the eastern United States though the coefficient of determination is only 0.15. Though significant, the depth can explain little of the maximum horizontal stress variation. Further, the maximum horizontal stress normalized by the elastic modulus does not increase significantly with depth. This implies that the elastic modulus can explain some of the variation attributed to depth and suggesting that depth may not be a significant independent factor.

The minimal affects of depth may be due to the limited range of depth with stress measurements being taken over too large of an area to establish a reliable depth factor for the eastern United States from this data set.

CHAPTER 9: SUMMARY AND CONCLUSIONS

In this study, the relationship between the horizontal stress magnitude and the elastic modulus and depth were examined based on stress measurements made at sites related to mining in bedded deposits in the eastern United States. Relationships between the horizontal stress and the elastic modulus and depth were evaluated by fitting linear regressions through the stress data. The stress data set was composed of 40 sites where the horizontal stress had been determined. Site depths ranged from 275 to 2,300 ft. This range does encompass most of the expected depths for underground limestone and coal mines in the eastern United States.

The stress data was divided geographically into 3 main groups that included the northern and central Appalachian regions and the eastern Mid-Continent region. Initially, an analysis was made of the Beckley coal seam in the central Appalachian region where an extensive horizontal stress measurement program was conducted in the late 1970's and early 1980's. Regional and more general models for the eastern United States were then developed or evaluated for both the elastic modulus and depth. As part of the study, the strains produced by the stress fields were also considered.

To establish a strong relationship between the maximum horizontal stress and the elastic modulus in the Beckley coal seam, the data had to be separated into high and low strain zones. Geographically, 13 of the sites are in two coterminous zones with 8 sites in the high strain zone and 5 sites in the low strain zone with these zones encompassing areas of tens to hundreds of square miles. However, the Beckley #2 Mine, with two high strain sites is separated from the high strain zone by the intervening low strain zone. In the Beckley seam analysis, the individual measurements were used in developing the regression models. Regression models for the high strain zone could explain 68 percent of the variation in the magnitude of the maximum horizontal stress with the elastic modulus. However, for the low strain zone, only 8 percent of the maximum horizontal stress variation could be explained by the elastic modulus. In part, in the low strain zone, the range of the elastic modulus was not sufficient to establish a more reliable model. For the minimum stress, the models could explain much less or little of the variation with the elastic modulus.

The horizontal strain fields across the eastern United States were also examined using the applied strains. For the eastern United States, the typical site average maximum applied horizontal strain ranges from 300 to 600 micro strains. Sites with maximum strains below about 300 micro strains appear to be in partial strain relief. The sites with maximum strains above 550 micro strains are found only in the central Appalachian region. Further, the central Appalachian region high strain zone has site strains between 700 to 970 micro strains.

Regionally, the average maximum applied horizontal strain for the eastern Mid-Continent region was 376 micro strains and for the northern Appalachian region 444 micro strains. The northern Appalachian region has strains that are about 20 percent higher than the other low strain regions including the low strain zone of the central Appalachian region. For the central Appalachian region, the low strain zone has an average maximum applied horizontal strain of 369 micro strains and the high strain zone has an average maximum applied horizontal strain of 836 micro strains. Clearly, there are some very high strain zones in the central Appalachian region that have not been seen in other regions of the eastern United States.

The standard deviations of the regional maximum horizontal strains are less than about 25 percent of the average strain. Therefore, the strain fields are sufficiently uniform over large areas in the eastern United States to establish adequate regression models for the maximum excess horizontal stress based on the elastic modulus. In the case of the eastern Mid-Continent and northern Appalachian regions, these areas appear to cover thousands or hundreds of thousand of square miles. In general, the horizontal strain fields in the eastern United States can be separated into high and low strain groups in large part by geographic location. These groupings form the basis for high and low strain model development.

The minimum applied horizontal strains are for the northern Appalachian region, 264 micro strains, for the eastern Mid-Continent region 71 micro strains, for the low strain central Appalachian zone, 168 micro strains and for the high strain central Appalachian zone 437 micro strains. Clearly, the eastern Mid-Continent region has the lowest minimum applied horizontal strain. The ratios of the maximum to minimum applied horizontal strain are for the eastern Mid-Continent region 5.3, for the northern

Appalachian region 1.68 and for the high strain central Appalachian zone 1.91. In general, the horizontal strain fields across the eastern United States are fairly biaxial with almost uniaxial strain conditions across the eastern Mid-Continent region. In general, but especially for the eastern Mid-Continent region, the standard deviation of the minimum applied horizontal strain is relatively much higher than the maximum applied horizontal strain when compared to the average strain. This results in the minimum horizontal stress being much less dependent on the elastic modulus.

Table 9-1. Regression models for the excess maximum and maximum horizontal stress versus the elastic modulus developed in study.

Model	Number of sites	Coefficient, K_1	Constant, K_2	Coefficient of determination, R^2
Central Appalachian Region (Maximum Horizontal Stress)				
Low strain	7	444	252	0.72
High strain	13	965	215	0.9
Northern Appalachian Region (Maximum Horizontal Stress)				
General	7	576	0	0.89
General	7	564	94	0.89
Eastern Mid-Continent Region (Maximum Horizontal Stress)				
General	11	445	0	0.87
General	11	375	393	0.91
Eastern United States (Excess Maximum Horizontal Stress)				
Low Strain[1]	25	460	0	0.83
Low Strain[2]	18	414	0	0.88
Low Strain[3]	7	531	0	0.87
High Strain	13	924	0	0.86

[1]All low strain sites from the eastern United States were used in the analysis.
[2]All sites from the eastern Mid-Continent and central Appalachian low strain zone are used in the analysis.
[3]Only sites from the northern Appalachian region are used in the analysis.

Regional models based on the three main regions were also developed for the variation of the horizontal stress with the elastic modulus. Table 9-1 gives these regional models. The regional models can explain between 72 to 91 percent of the variation of the maximum horizontal stress. Like the Beckley seam, the central Appalachian region was divided into low and high strain zones with models developed for each. However, the geographic extent of these zones within the region is not entirely clear. These regional

models were established using site average values. Using individual measurements in the analysis will decrease the coefficients of determination because of the local and site variation in the strain field.

For specific mines or groups of sites, strong relationships between the elastic modulus and the maximum horizontal stress were also found. In general, these are groups of sites or mines where there is a sufficient range of the elastic modulus and also a sufficiently uniform strain field. To establish a reliable model does in general require a large enough range in the elastic modulus.

High and low strain models for the variation of the maximum excess horizontal stress with the elastic modulus were also developed for the eastern United States (table 9-1). Because the northern Appalachian region had strains that were about 20 percent higher, two low strain models were developed. One low strain model incorporates the eastern Mid-Continent region and the central Appalachian region low strain zone, the other, the northern Appalachian region. The high strain model encompasses the high strain zone of the central Appalachian region. However, the exact geographic outline of the high and low strain zones in the central Appalachian region is not clearly defined. The models can explain between 83 to 88 percent of the variation of the maximum excess horizontal stress with the elastic modulus. The coefficients of the elastic modulus in the models range from between 414 to 531 micro strains for the low strain models to 924 micro strains for the high strain model. These model coefficients can be considered the strain produced from the tectonic or maximum excess horizontal stress.

In general, the relationship between the elastic modulus and the minimum horizontal stress is much weaker or almost non-existent with the minimum stress not as dependent on the elastic modulus. This is reflected in the difference and variability of the maximum to minimum horizontal stress and strain ratios within and between regions. To have a minimum horizontal stress as dependent on the elastic modulus as the maximum stress would require that the ratios be nearly constant. The minimum horizontal stress being less dependent on the elastic modulus is in part due to the lower average strains and the higher standard deviation of those strains relative to the average strain. This is especially true in the eastern Mid-Continent region where the standard deviation actually

exceeds the minimum average applied horizontal strain. Essentially, in the eastern Mid-Continent region the minimum applied horizontal strain variation is so large as to preclude a sufficiently uniform strain field to develop adequate models. This results from the low average minimum horizontal strain across the region. Where there is a higher minimum applied horizontal strain with a lower standard deviation such as in the northern Appalachian region, the minimum horizontal stress is almost as dependent on the elastic modulus as the maximum horizontal stress.

From the regional analysis, no significant increase in the maximum horizontal stress with depth was observed. The depth could explain very little of the variation in the horizontal stress across any region. Further, the horizontal strains from the maximum horizontal stress do not significantly increase for any of the regions. For the eastern United States, the maximum horizontal stress does appear to increase significantly with depth though the depth could explain only 15 percent of the variation. However, there was no statistically significant increase in the strain from the maximum horizontal stress with depth and no regional increase in the maximum horizontal stress with depth, thus the cause of this statistically significant increase appears to be in part the regional differences in the other parameters such as the elastic modulus and the strain level. Further, for this data, there is some correlation between depth and the elastic modulus, though this correlation is weak, it is sufficient to result in the maximum horizontal stresses normalized by the elastic modulus not increasing significantly with depth. The depth analysis though, must be put into context where the range of depths from the sites was from 275 to 2,300 feet. This may not be a sufficient depth range with the sites located across such a wide geographic area to be able to develop an adequate or appropriate depth factor. Because the strain did not increase significantly with depth, the depth cannot in general be used as an independent variable in the models. However, if the strain did increase with depth, then the strains and the affects of the elastic modulus will be dependent in part on depth. Essentially, multiple regression models cannot be developed with both the elastic modulus and depth as independent variables. Further, none of the multiple regression analysis indicated that depth was a significant factor.

Theoretically, there is a basis for an increase in the horizontal stress with depth based on gravity and Poisson's effect. This effect is not dependent on any increase in the applied

horizontal strains. However, if this effect does exist, the magnitude of this increase is too small to measure within the present data set. Because of regional differences in the average depth, elastic modulus and strain fields and because the affects of the elastic modulus over shadow the depth effects, no adequate depth factor could be established for the eastern United States.

The main conclusions drawn from this study are:

1. The variation of the magnitude of the maximum horizontal stress is strongly dependent on the elastic modulus across the eastern United States.

2. The horizontal strain fields are sufficiently uniform across large geographic sections of the eastern United States to allow for models to be developed for the variation of the maximum horizontal stress based on the elastic modulus that can be applied to these regions. Essentially, in this data set, the horizontal strains are more uniform than the horizontal stresses.

3. A very high strain zone does exist in the central Appalachian region that includes a portion of the Beckley coal seam though the exact extent of the zone is not known.

4. The minimum horizontal stress and strain in the eastern Mid-Continent region are much less than for the central and Northern Appalachian regions. Further, the horizontal stresses are much more biaxial or directional in the eastern Mid-Continent region.

5. The minimum horizontal stress variation is in general less dependent on the elastic modulus than the maximum horizontal stress. This is due in large part to the lower average minimum horizontal strains and the relatively higher standard deviation of the strain. This can be seen in the eastern Mid-Continent region with a standard deviation that is larger than the average applied horizontal strain.

6. Although the depth did cause a significant increase in the maximum horizontal stress across the eastern United States, the depth did not cause a significant increase in the strains from the maximum horizontal stress. Therefore, depth cannot be used independently of the elastic modulus and strain in the development of the regression models for this data set. Essentially, the elastic modulus can

explain the variations of the stress that could be attributed to depth in this data set. However, a theoretical basis is used in this study based on Poisson's effect and gravity though this effect is small. Further, the development of an adequate depth factor may require a greater depth range than found in the data set.

7. The elastic modulus of the rock utilizing the developed regression models provides a much better estimate of the maximum horizontal stress variation than does the depth in this data set.

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Appendix A

Table A-1. Measured horizontal stresses in the Beckley coal field.

Mine	Hole	Measurement depth, ft	Maximum horizontal stress, psi	Minimum horizontal stress, psi	Maximum[1] horizontal strain, micro strain	Minimum[1] horizontal strain, micro strain	Elastic modulus, 10^6 psi	Site depth, ft
Beckley #4	1	18	1484	1141	838	645	1.77	820
Beckley #1	2	5.2	3306	1738	396	208	8.34	1130
Beckley #1	2	9.2	3152	1983	507	319	6.22	1130
Beckley #1	2	14.4	3184	1961	434	268	7.33	1130
Beckley #2	3	10.2	2317	1689	1048	764	2.21	1100
Beckley #2	3	12.3	2416	1725	1046	747	2.31	1100
Bonny	4	14.7	4390	3335	1237	939	3.55	1136
Bonny	4	16	3175	2845	971	870	3.27	1136
Bonny	4	18.4	2933	1972	776	522	3.78	1136
Bonny	4	19.6	3451	2689	920	717	3.75	1136
Bonny	5	15.8	5047	2389	950	450	5.31	1148
Bonny	5	16.8	5816	3061	1028	541	5.66	1148
Bonny	5	22.3	8264	5062	1176	720	7.03	1148
Maple Meadows	6	15.4	2383	2141	391	351	6.1	708
Maple Meadows	6	16.1	3022	2896	471	452	6.41	708
Maple Meadows	6	17.7	2862	2792	442	432	6.47	708
Maple Meadows	7	15.3	4615	2969	972	625	4.75	735
Maple Meadows	7	16.8	4594	3325	1531	1108	3	735
Maple Meadows	7	24.4	3900	2449	701	440	5.56	735
Maple Meadows	8	21	3901	2110	601	325	6.49	1025
Maple Meadows	8	22	4648	2478	714	381	6.51	1025
Maple Meadows	8	23	4177	2492	506	302	8.26	1025

Table A-1. Measured horizontal stresses in the Beckley coal field (Cont.).

Mine	Hole	Measurement depth, ft	Maximum horizontal stress, psi	Minimum horizontal stress, psi	Maximum[1] horizontal strain, micro strain	Minimum[1] horizontal strain, micro strain	Elastic modulus, 10^6 psi	Site depth, ft
Maple Meadows	9	9.1	2636	1597	1094	663	2.41	814
Maple Meadows	9	12	2893	2025	1162	813	2.49	814
Maple Meadows	9	13.5	3058	2105	1307	900	2.34	814
Maple Meadows	9	14.5	3705	2692	1506	1094	2.46	814
Maple Meadows	9	18.8	3344	3019	1348	1217	2.48	814
Maple Meadows	9	19.3	3456	2652	1345	1032	2.57	814
Maple Meadows	10	18.7	3939	1584	566	228	6.96	807
Maple Meadows	10	19.7	2860	1465	423	217	6.76	807
Maple Meadows	10	20.7	3138	1646	433	227	7.24	807
Maple Meadows	10	22.9	3356	1892	501	282	6.7	807
Beckley Mining	11	10.3	2711	2261	812	677	3.34	640
Beckley Mining	11	15.7	3385	1206	898	319	3.78	640
Beckley Mining	11	16.7	3303	3069	1032	959	3.2	640
Beckley Mining	11	22.2	3146	2362	1183	888	2.66	640
Beckley Mining	11	23.2	3287	2649	1417	1142	2.32	640
Beckley Mining	11	24.8	2596	1991	1086	833	2.39	640
Beckley Mining	12	15.1	4202	3598	1281	1097	3.28	870
Beckley Mining	12	16.5	3690	2958	1186	951	3.11	870
Beckley Mining	12	20.3	3819	2743	1265	908	3.02	870
Beckley Mining	12	21.8	3538	2630	1320	981	2.68	870
Beckley Mining	12	22.8	3391	2629	1309	1015	2.59	870
Beckley Mining	13	13.8	3416	2433	1251	891	2.73	800
Beckley Mining	13	18.2	3746	2935	1283	1005	2.92	800
Beckley Mining	13	20.7	2701	1995	1159	856	2.33	800
Beckley Mining	13	23.3	2772	1949	943	663	2.94	800

Table A-1. Measured horizontal stresses in the Beckley coal field (Cont.).

Mine	Hole	Measurement depth, ft	Maximum horizontal stress, psi	Minimum horizontal stress, psi	Maximum[1] horizontal strain, micro strain	Minimum[1] horizontal strain, micro strain	Elastic modulus, 10^6 psi	Site depth, ft
Beckley Mining	13	24.5	2927	2193	1166	874	2.51	800
Beckley Mining	13	25.5	3566	2916	1278	1045	2.79	800
Beckley Mining	14	16.3	4209	2563	1213	739	3.47	1040
Beckley Mining	14	17.4	3664	2312	1186	748	3.09	1040
Beckley Mining	14	18.4	3581	1993	1066	593	3.36	1040
Beckley Mining	14	22.6	3426	2134	999	622	3.43	1040
Beckley Mining	14	24.2	4132	2401	991	576	4.17	1040
Beckley #1	15	9.5	3221	1879	419	244	7.69	700
Beckley #1	15	10.7	3672	2170	488	289	7.52	700
Beckley #1	15	13.6	2144	1227	317	182	6.76	700
Beckley #2	16	12	1852	1447	1001	782	1.85	350
Beckley #2	16	13.1	1711	1324	1012	783	1.69	350
Beckley #2	16	14.2	1814	1297	1099	786	1.65	350
Beckley #2	16	15.25	1887	1281	1123	763	1.68	350

[1]The horizontal strains are from the maximum and minimum stresses.

Table A-2. Excess horizontal stresses and strains in the Beckley coal field.

Mine	Hole	Measurement depth, ft	Maximum horizontal stress, psi	Minimum horizontal stress, psi	Maximum[1] horizontal strain, micro strain	Minimum[1] horizontal strain, micro strain	Elastic modulus, 10^6 psi	Site depth, ft
Beckley #4	1	18	1186	843	670	476	1.77	820
Beckley #1	2	5.2	2896	1328	347	159	8.34	1130
Beckley #1	2	9.2	2742	1573	441	253	6.22	1130
Beckley #1	2	14.4	2774	1551	378	212	7.33	1130
Beckley #2	3	10.2	1918	1290	868	584	2.21	1100
Beckley #2	3	12.3	2017	1326	873	574	2.31	1100
Bonny	4	14.7	3978	2923	1121	823	3.55	1136
Bonny	4	16	2763	2433	845	744	3.27	1136
Bonny	4	18.4	2521	1560	667	413	3.78	1136
Bonny	4	19.6	3039	2277	810	607	3.75	1136
Bonny	5	15.8	4630	1972	872	371	5.31	1148
Bonny	5	16.8	5399	2644	954	467	5.66	1148
Bonny	5	22.3	7847	4645	1116	661	7.03	1148
Maple Meadows	6	15.4	2126	1884	349	309	6.1	708
Maple Meadows	6	16.1	2765	2639	431	412	6.41	708
Maple Meadows	6	17.7	2605	2535	403	392	6.47	708
Maple Meadows	7	15.3	4348	2702	915	569	4.75	735
Maple Meadows	7	16.8	4327	3058	1442	1019	3	735
Maple Meadows	7	24.4	3633	2182	653	392	5.56	735
Maple Meadows	8	21	3529	1738	544	268	6.49	1025
Maple Meadows	8	22	4276	2106	657	324	6.51	1025
Maple Meadows	8	23	3805	2120	461	257	8.26	1025
Maple Meadows	9	9.1	2341	1302	971	540	2.41	814
Maple Meadows	9	12	2598	1730	1043	695	2.49	814

Table A-2. Excess horizontal stresses and strains in the Beckley coal field. (Cont.)

Mine	Hole	Measurement depth, ft	Maximum horizontal stress, psi	Minimum horizontal stress, psi	Maximum[1] horizontal strain, micro strain	Minimum[1] horizontal strain, micro strain	Elastic modulus, 10^6 psi	Site depth, ft
Maple Meadows	9	13.5	2763	1810	1181	774	2.34	814
Maple Meadows	9	14.5	3410	2397	1386	974	2.46	814
Maple Meadows	9	18.8	3049	2724	1229	1098	2.48	814
Maple Meadows	9	19.3	3161	2357	1230	917	2.57	814
Maple Meadows	10	18.7	3646	1291	524	185	6.96	807
Maple Meadows	10	19.7	2567	1172	380	173	6.76	807
Maple Meadows	10	20.7	2845	1353	393	187	7.24	807
Maple Meadows	10	22.9	3063	1599	457	239	6.7	807
Beckley Mining	11	10.3	2479	2029	742	607	3.34	640
Beckley Mining	11	15.7	3153	974	834	258	3.78	640
Beckley Mining	11	16.7	3071	2837	960	887	3.2	640
Beckley Mining	11	22.2	2914	2130	1095	801	2.66	640
Beckley Mining	11	23.2	3055	2417	1317	1042	2.32	640
Beckley Mining	11	24.8	2364	1759	989	736	2.39	640
Beckley Mining	12	15.1	3886	3282	1185	1001	3.28	870
Beckley Mining	12	16.5	3374	2642	1085	850	3.11	870
Beckley Mining	12	20.3	3503	2427	1160	804	3.02	870
Beckley Mining	12	21.8	3222	2314	1202	863	2.68	870
Beckley Mining	12	22.8	3075	2313	1187	893	2.59	870
Beckley Mining	13	13.8	3126	2143	1145	785	2.73	800
Beckley Mining	13	18.2	3456	2645	1184	906	2.92	800
Beckley Mining	13	20.7	2411	1705	1035	732	2.33	800
Beckley Mining	13	23.3	2482	1659	844	564	2.94	800

Table A-2. Excess horizontal stresses and strains in the Beckley coal field. (Cont.)

Mine	Hole	Measurement depth, ft	Maximum horizontal stress, psi	Minimum horizontal stress, psi	Maximum[1] horizontal strain, micro strain	Minimum[1] horizontal strain, micro strain	Elastic modulus, 10^6 psi	Site depth, ft
Beckley Mining	13	24.5	2637	1903	1051	758	2.51	800
Beckley Mining	13	25.5	3276	2626	1174	941	2.79	800
Beckley Mining	14	16.3	3831	2185	1104	630	3.47	1040
Beckley Mining	14	17.4	3286	1934	1063	626	3.09	1040
Beckley Mining	14	18.4	3203	1615	953	481	3.36	1040
Beckley Mining	14	22.6	3048	1756	889	512	3.43	1040
Beckley Mining	14	24.2	3754	2023	900	485	4.17	1040
Beckley #1	15	9.5	2967	1625	386	211	7.69	700
Beckley #1	15	10.7	3418	1916	455	255	7.52	700
Beckley #1	15	13.6	1890	973	280	144	6.76	700
Beckley #2	16	12	1724	1319	932	713	1.85	350
Beckley #2	16	13.1	1583	1196	936	706	1.69	350
Beckley #2	16	14.2	1686	1169	1022	708	1.65	350
Beckley #2	16	15.25	1759	1153	1047	686	1.68	350

[1]The strains are from the maximum and minimum excess horizontal stresses.

Table B-1. Measured and excess horizontal stresses and strains in the central Appalachian region (excluding the Beckley coal field).

Site	Measurement depth, ft	Maxi. horizontal stress, psi	Min. horizontal stress, psi	Direction of max. stress	Elastic modulus, 10^6 psi	Depth, ft	Max. strain, micro strain	Min. strain, micro strain	Max. excess stress, psi	Min. excess stress, psi	Max. excess strain, micro strain	Min. excess strain, micro strain	Used in general analysis
Pocahontas #4-1	5.8	2800	1800	N 54 °E	3.1	1600	903	581	2219	1219	716	393	No
Pocahontas #4-1	12.9	3300	2400	N 62 °E	3.59	1600	919	669	2719	1819	757	507	Yes
Pocahontas #4-2	2.3	3100	900	N 67 °E	3.8	1250	816	237	2646	446	696	117	No
Pocahontas #4-2	3.8	2400	1300	N 78 °E	2.52	1250	952	516	1946	846	772	336	No
Pocahontas #4-2	5.2	3000	1700	N 71 °E	3.23	1250	929	526	2546	1246	788	386	No
Pocahontas #4-2	6.6	2600	1400	N 67 °E	3.59	1250	724	390	2146	946	598	264	No
Pocahontas #4-2	8	3000	1900	N 64 °E	4.01	1250	748	474	2546	1446	635	361	Yes
Pocahontas #4-2	11.8	2200	1100	N 29 °W	2.48	1250	887	444	1746	646	704	260	Yes
Eagle Seam	8.9	1781	1541	N 40 °E	2.99	900	596	515	1454	1214	486	406	Yes
Eagle Seam	9.9	1832	1440	N 56 °E	2.82	900	650	511	1505	1113	534	395	Yes
Eagle Seam	10.9	1678	1109	N 47 °E	3.03	900	554	366	1351	782	446	258	Yes
Elkhorn #3	13.7-23.4	2269	1822	N 56 °E	5.24	550	433	348	2069	1622	395	310	Yes

APPENDIX C

Table C-1. Measured and excess horizontal stresses and strains in the northern Appalachian region.

Site	Measurement depth, ft	Maxi. horizontal stress, psi	Min. horizontal stress, psi	Max. excess stress, psi	Min. excess stress, psi	Max. horizontal strain, micro strain	Min. horizontal strain, micro strain	Min. excess strain, micro strain	Min. excess strain, micro strain	Elastic modulus, 10^6 psi	Depth, ft
Tanoma, PA-Kittanning Seam	16.1	3335	2787	3074	2526	575	481	530	436	5.8	720
Phillippi, WV-Kittanning Seam	15.3	4279	2861	4079	2661	718	480	684	446	5.96	550
Phillippi, WV-Kittanning Seam	18.3	1664	1344	1464	1144	633	511	557	435	2.63	550
Phillippi, WV-Kittanning Seam	18.7	1316	1151	1116	951	823	719	698	594	1.6	550
Phillippi, WV-Kittanning Seam	23.1	4959	3525	4759	3325	714	507	685	478	6.95	550
Loyalhanna Formation, PA	10-12	6910	3975	6765	3830	617	355	604	342	11.2	400
Columbus Limestone, OH	-	5500	4000	4665	3165	611	444	518	352	9	2300
Pittsburgh Seam Site 1	13-20	1324	1024	1179	879	736	569	655	488	1.8	400
Pittsburgh Seam Site 2	11	2400	2190	2146	1936	588	537	526	475	4.08	700
Pittsburgh Seam Site 2	13	2480	2260	2226	2006	525	479	472	425	4.72	700
Pittsburgh Seam Site 3	17	4210	2540	3920	2250	543	327	505	290	7.76	800
Pittsburgh Seam Site 3	18.5	3590	2340	3300	2050	418	273	385	239	8.58	800
Pittsburgh Seam Site 3	19.8	2790	2110	2500	1820	421	319	378	275	6.62	800
Average		-	-	-	-	609	462	554	406	-	-

[1]Strains from the maximum or minimum horizontal stress component.

Table D-1. Measured and excess horizontal stresses and strains in the Illinois Basin and eastern Mid-Continent region.

Hole	Measurement depth, ft	Maxi. horizontal stress, psi	Min. horizontal stress, psi	Direction of max. stress	Elastic modulus, 10^6 psi	Max. strain, micro strain	Min. strain, micro strain	Depth, ft	Max. excess stress, psi	Min. excess stress, psi	Max. excess strain, micro strain	Min. excess strain, micro strain	Used in general analysis
					Wabash Mine, IL, Springfield #5 Seam								
1	10.7	1134	965	N 44 °E	3.15	360	306	970	782	613	248	195	Yes
1	12.1	1313	867	N 79 °W	3.37	390	257	970	961	515	285	153	Yes
1	13.5	1362	1030	N 89 °E	2.96	460	348	970	1010	678	341	229	Yes
1	16.5	1274	888	N 88 °W	2.97	429	299	970	922	536	310	180	Yes
2	8.4	1533	949	N 89 °E	3.39	452	280	850	1224	640	361	189	No
2	9.9	1606	981	N 81 °E	3.13	513	313	850	1297	672	415	215	Yes
2	14.1	1423	768	N 76 °E	2.94	484	261	850	1114	459	379	156	Yes
2	15.8	1263	735	N 84 °E	2.63	480	279	850	954	426	363	162	Yes
3	7.2	1451	670	N 82 °W	3.33	436	201	860	1139	358	342	107	No
3	8.4	1599	572	N 89 °W	2.94	544	195	860	1287	260	438	88	No
3	9.9	1405	589	N 72 °W	2.82	498	209	860	1093	277	388	98	Yes
3	13.1	1493	559	N 69 °W	2.78	537	201	860	1181	247	425	89	Yes
3	14.4	1356	540	N 77 °W	2.82	481	191	860	1044	228	370	81	Yes
3	15.9	1606	643	N 81 °W	2.99	537	215	860	1294	331	433	111	Yes
					Monterey Mine, IL, Springfield#5 Seam								
1	4.33	2277	707	N 59 °E	7.83	291	90	290	2172	602	277	77	No
1	6.33	905	238	N 66 °E	2.47	366	96	290	800	133	324	54	No
1	9.4	1148	728	N 69 °E	1.9	604	383	290	1043	623	549	328	Yes
1	11.8	636	410	N 55 °E	1.44	442	285	290	531	305	369	212	Yes
					Galatia Mine, IL, Springfield #5 Seam								
1	6	1448	388	N 78 °E	2.9	499	134	570	1241	181	428	62	No
1	10.1	1980	586	N 72 °E	3.17	625	185	570	1773	379	559	120	Yes
1	11.6	1674	467	N 77 °E	2.91	575	160	570	1467	260	504	89	Yes

Table D-1. Measured and excess horizontal stresses and strains in the Illinois Basin and eastern Mid-Continent region. (Cont.)

Hole	Measurement depth, ft	Maxi. horizontal stress, psi	Min. horizontal stress, psi	Direction of max. stress	Elastic modulus, 10^6 psi	Max. strain, micro strain	Min. strain, micro strain	Depth, ft	Max. excess stress, psi	Min. excess stress, psi	Max. excess strain, micro strain	Min. excess strain, micro strain	Used in general analysis
1	13.1	1654	533	N 71 °E	2.81	589	190	570	1447	326	515	116	Yes
Turris Mine, IL, Springfield #5 Seam													
1	6.1	2208	1122	N 38 °E	9.05	244	124	275	2108	1022	233	113	No
2	5.8	1846	814	N 61 °E	8.08	228	101	275	1746	714	216	88	No
Peabody # 10, Il, Herrin #6 Seam													
1	3	1293	409	N 39 °E	5.52	234	74	360	1162	278	211	50	No
1	4	1582	-24	N 52 °E	9	176	-3	360	1451	-155	161	-17	No
1	5	2490	46	N 65 °E	5.46	456	8	360	2359	-85	432	-16	No
1	6	2435	-458	N 66 °E	6.62	368	-69	360	2304	-589	348	-89	No
1	7	3588	371	N 67 °E	7.37	487	50	360	3457	240	469	33	No
1	8	2519	-85	N 65 °E	5.64	447	-15	360	2388	-216	423	-38	No
1	9	1227	1041	East West	1.56	787	667	360	1096	910	703	584	Yes
1	10	835	518	N 79 °E	1.28	652	405	360	704	387	550	303	Yes
1	11	3379	749	N 67 °E	5.7	593	131	360	3248	618	570	108	Yes
Peabody # 2, KY , Springfield #5 Seam													
1	3.5	1146	994	N 16 °E	2	573	497	300	1037	885	519	443	No
1	4.92	1251	1167	N 40 °E	2.4	521	486	300	1142	1058	476	441	No
1	6.67	1613	1575	N 82 °E	3	538	525	300	1504	1466	501	489	No
1	21	969	896	N 81 °E	2.2	440	407	300	860	787	391	358	Yes
Ft. Campbell Limestone, Campbell County, KY													
NA	NA	3784	1320	N 78 °E	9.32	406	142	730	3519	1055	360	43	Yes
Immel Mine, TN													
3	8.8	4609	1980	N 65 °E	10.75	429	184	925	4273	1644	405	161	Yes
3	14.2	4203	818	N 59 °E	11.36	370	72	925	3867	482	348	50	Yes
4	13.7	2354	1518	N 65 °E	7.28	323	208	925	2018	1182	288	174	Yes

Table D-1. Measured and excess horizontal stresses and strains in the Illinois Basin and eastern Mid-Continent region. (Cont.)

Hole	Measurement depth, ft	Maxi. horizontal stress, psi	Min. horizontal stress, psi	Direction of max. stress	Elastic modulus, 10^6 psi	Max. strain, micro strain	Min. strain, micro strain	Depth, ft	Max. excess stress, psi	Min. excess stress, psi	Max. excess strain, micro strain	Min. excess strain, micro strain	Used in general analysis
4	15.7	3647	1543	N 42 °E	4.64	786	333	925	3311	1207	731	278	Yes
4	16.7	3248	825	N 67 °E	11.94	272	69	925	2912	489	251	48	Yes
4	18.7	3352	720	N 58 °E	7.3	459	99	925	3016	384	424	64	Yes
4	19.7	2805	1469	N 70 °E	5.58	502	263	925	2469	1133	457	218	Yes
4	20.8	2503	996	N 71 °E	4.86	515	205	925	2167	660	463	153	Yes
					North River, AL, Pratt Seam								
1	7.25	2404	404	N 54 °E	5.91	407	68	500	2223	223	376	38	Yes
1	8.4	2050	391	N 58 °E	5.11	401	77	500	1869	210	366	41	Yes
1	9.4	1849	117	N 54 °E	5.4	342	22	500	1668	-65	309	-12	Yes
1	11.25	2163	261	N 63 °E	5.26	411	50	500	1982	80	377	15	Yes
2	6.5	647	306	N 69 °E	4.38	148	70	470	476	135	109	31	No
2	7.6	1032	485	N 71 °E	5.12	202	95	470	861	314	168	61	No
2	8.6	1015	197	N 69 °E	4.59	221	43	470	844	26	184	6	No
2	9.6	1081	469	N 66 °E	4.45	243	105	470	910	298	205	67	No
					Jim Walters #7, AL, Blue Creek/Mary Lee Seam								
NA	NA	3050	1520	N 71 °E	5.4	565	281	1870	2364	834	439	156	Yes

[1]Strains from the maximum or minimum stress component.