Possible Mechanism for Surface Vibrations Near Maxwell Hill, West Virginia

ANTHONY IANNACCHIONE, Supervisory Geologist
CHRISTOPHER MARK, Mining Engineer
U. S. Bureau of Mines, P.O. Box 18070, Pittsburgh, PA 15236

ABSTRACT

Residents of Maxwell Hill, a suburb of Beckley, West Virginia, reported from January until March of 1988 a series of earth tremors. The tremors rattled dishes, and the noises associated with tremors were sometimes loud enough to wake people at night. These events were puzzling because Beckley is in an area of low seismic activity. Maxwell Hill is located above abandoned coal mines, though no direct subsidence damage to surface structures has been documented. A research program was initiated to determine whether subsurface ground movements associated with the abandoned mines could be responsible for the seismic activity experienced at the surface.

A hypothesis is proposed which states that seismic disturbances can be caused by abandoned mine failure when two conditions are met. First, some instability must exist at the mine level. The most likely cause of instability is the failure of pillars of coal that were left for support at the time of mining. Second, subsurface movements can result in significant seismic activity only when the rock above the mine contains at least one very strong and brittle layer that is prone to fail violently through rupture or fault slip movement. Analysis of the data indicates that both hypothesized conditions for mine-related seismicity appear to have been satisfied in the case of Maxwell Hill. It has therefore been concluded that the earth tremors experienced by Maxwell Hill residents probably are related to the abandoned mines. Analysis of the potential magnitude of these events indicates that they are unlikely to cause significant surface damage. The probability that future events will disturb the residence of Maxwell Hill should be quite low based on the identified mechanism.

INTRODUCTION

Any time mining takes place underground, a void is created where the material had been; and through the force of gravity and the release of stress in the surrounding rocks, mine voids tend to fill soon after they are created. The response of the rock mass to mining can take many forms, including seismic events that can propagate to the surface as noise and! or vibrations.

Residents of Maxwell Hill, a residential community located approximately two miles north of the business district of Beckley, were disturbed by a number of earth tremors during January, February and March of 1988. The vibrations from these events, which were likened to "explosions", were reported to have awakened families at night and to have knocked dishes off china closets. Table 1 lists the observations of one resident who recorded 10 significant events, ranging from III to IV on the Modified Mercalli Scale, during this three month interval (Eltschlager, 1988). Intensity scales, such as the Modified Mercalli scale, 1956 version (Richter, 1956), are used to rate the amount of disturbance and damage to man, civil structures, and the natural environment that result from seismic events. Preliminary investigations of these events carried out by the Office of Surface Mining reported that no active mines occurred in this area nor did these times correspond to blast from quarries, strip mines or construction sites. The investigation also disputed a claim by one property owner of structural damage caused by the seismic events. The Bureau of Mines was asked to determine whether these seismic events could be related to subsurface movements associated with the abandoned mines.

Mining induced seismic events from active coal and hard rock mines have been well documented and are summarized by Gibowicz (1988) and Hasegawa and others (1989). These authors indicate several mechanisms are responsible for the seismicity including: cavity collapse, pillar burst, fracture propagation and fault slip movement. Several of these conditions responsible for mining-induced seismicity may also exist in abandoned coal mine. For example, coal pillars in abandoned mines may deteriorate over time and eventually be overstressed and failing. Local pillar collapse can cause ground stresses to shift to adjacent pillars and temporarily altering the stability around the mining section. The widespread effects of pillar failure on regional mine stability have been observed in prior Bureau studies (Campoli et aI., 1987). However, the amount of seismic energy released directly from the coal during pillar failure is generally quite low due to the large dissipation of energy into the mine opening.

Greater seismic events can result from the failure of the strata surrounding mines. Large volumes of massive, highly stressed rock can accumulate tremendous amounts of strain energy. The collapse of the supporting pillars can cause the strain energy to be released suddenly. Long and Copeland (1989) reported that a seismic event of magnitude 3.6 occurred in association with pillar failure and a major roof collapse in an active Alabama longwall coal mine. Therefore, these two hypothetical conditions, instability at mine level and movement or rupture of brittle rock above the mine, are thought

Table 1. *Observations of surface vibrations.*

DATE	TIME	COMMENTS
01/21/88	10:37 pm	Felt largest explosion yet; so did neighbors. with little ones following
01/22/88	4:35 pm	Large vibration
01/25/88	3:35 am	Large vibration
01/28/88	4:07 am	Large vibration
01/29/88	3:30 pm	Large vibration
01/30/88	4:00 pm	Large vibration
02/06/88	12:38 pm	Very large vibration and explosion
02/16/88		Very long (15 seconds) vibration
02/20/88	3:59 pm	Large vibration

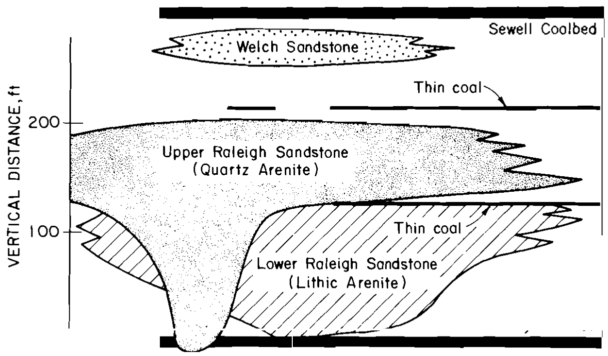
to be necessary for surface seismicity to occur. The goal of this paper is to a) determine whether the two critical conditions exist in the vicinity of Maxwell Hill, b) estimate the probability for surface damage, and c) determine if similar events may occur in the future. It is also hoped that some of the improprieties associated with using standard earthquake techniques for analyzing mine-induced events can be characterized.

GEOLOGY

The generalized geologic section for the Maxwell Hill area, Figure 1, indicates the coal-bearing strata includes massive sandstones, as well as interbedded sandstones, shales, siltstones, claystones and coalbeds. Two coalbeds, the Sewell and the Beckley, have been mined beneath Maxwell Hill. The shallow Sewell Coalbed was mined first; and the deeper Beckley Coalbed was mined most recently. Figure 2 shows that the depth of the Beckley Coalbed in the Maxwell Hill area ranges between 550 and 700 ft (168 to 213 m). The interval between the two seams, shown in Figure 3, varies between 250 and 300 ft (76 to 91 m).

Borehole analysis and outcrop examinations indicate that the most massive rock layers in the region are the Upper and Lower Raleigh Sandstones, located between the Beckley and Sewell mining horizons. The strata between the Sewell and the surface appears not to contain massive beds; and the sandstones present above the Sewell horizon disaggregate readily when observed in outcrops.

The strata in the Beckley area dip uniformly to the northwest 3 degrees, bringing the two coalbeds to the surface east of Maxwell Hill (Figure 4). This structural dip is responsible for the increase in depth of cover to the northwest, shown on Figure 3.



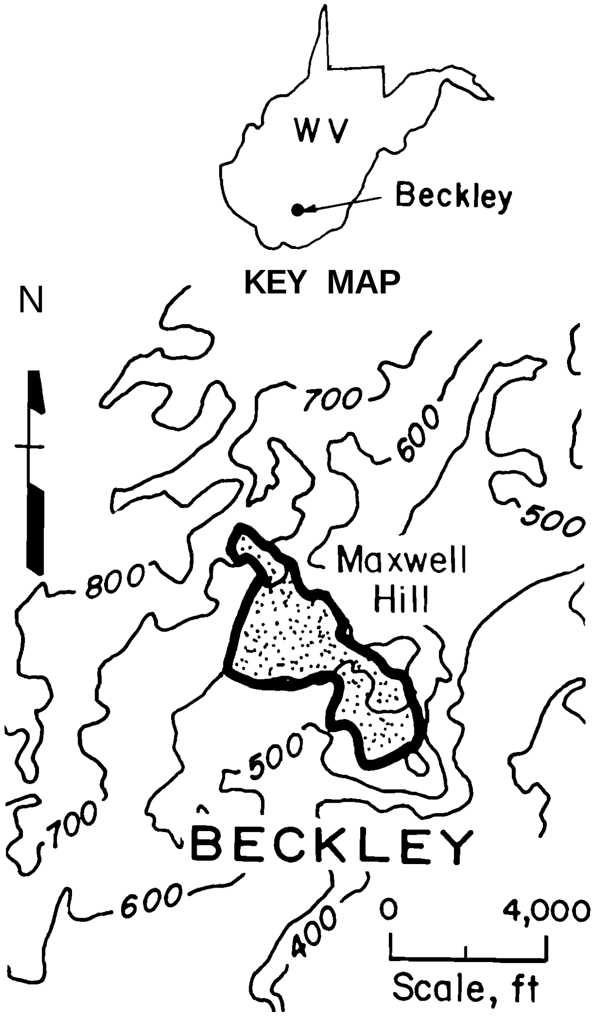


Figure 2. Overburden above the Beckley Coalbed; contour interval = 100 ft.

MINE STRUCTURE STABILITY

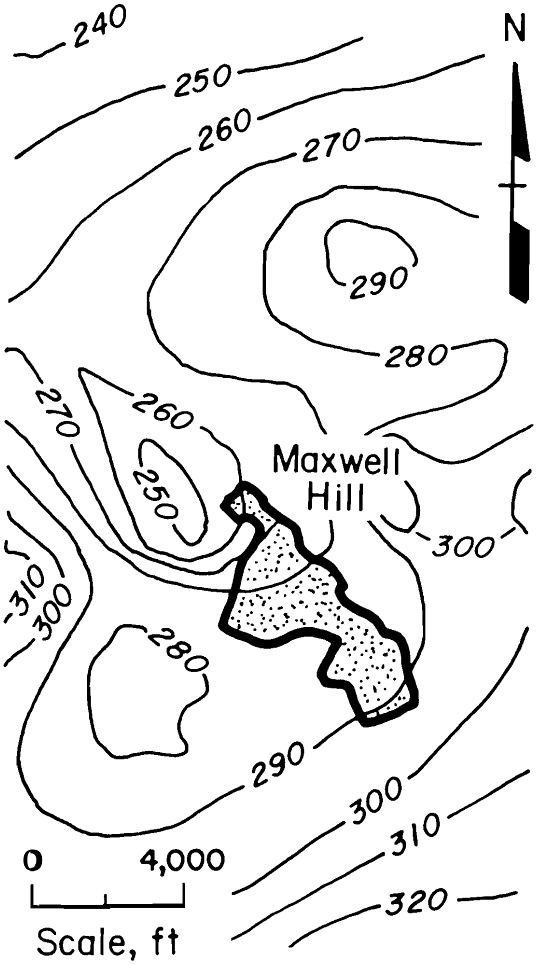


Figure 3. Thickness of the interval between Sewell and Beckley Coalbeds; contour intervals = 10 ft.

cause a seismic disturbance, because the energy would be released in small increments continuously over time as the strata gradually adjusted to the newly created void. On the other hand, if weak pillars fail and remove support to the roof (Craft and Crandall, 1988), a strong roof could become more highly strained until it finally collapsed. Such a collapse could release a large amount of energy and possibly cause a seismic disturbance. The focus of our analysis will therefore be on the possibility of pillar failure.

Pillar failure occurs when the applied load exceeds the pillar strength. The load is applied to the pillar by the weight of the rock between the mine and the surface (Mark, 1987). Where pillars have been spaced on a regular basis, the load on each may be estimated using "tributary area theory" (Figure 5A).

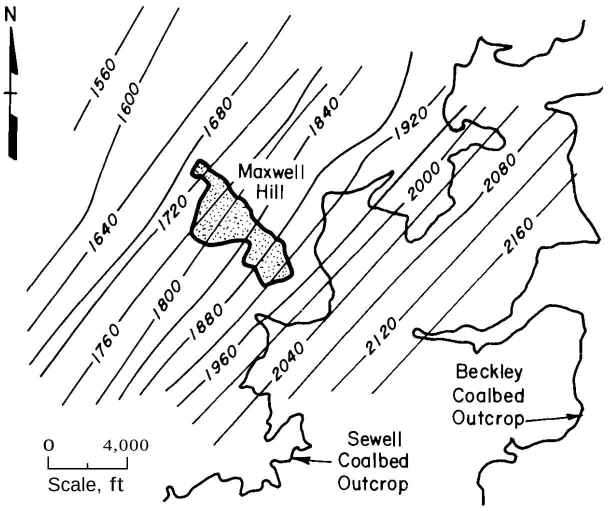


Figure 4. Structure contour of the Beckley Coalbed; structure contours = 40 ft.

According to the tributary area theory, the pillar load is inversely proportional to the percentage of coal extraction. If the pillars have been left next to a gob area (an area where the coal has been completely extracted) then the total pillar load includes a component of the "abutment load" (Figure 5B). The abutment angle defines a wedge of strata whose weight is transferred to the adjacent pillar.

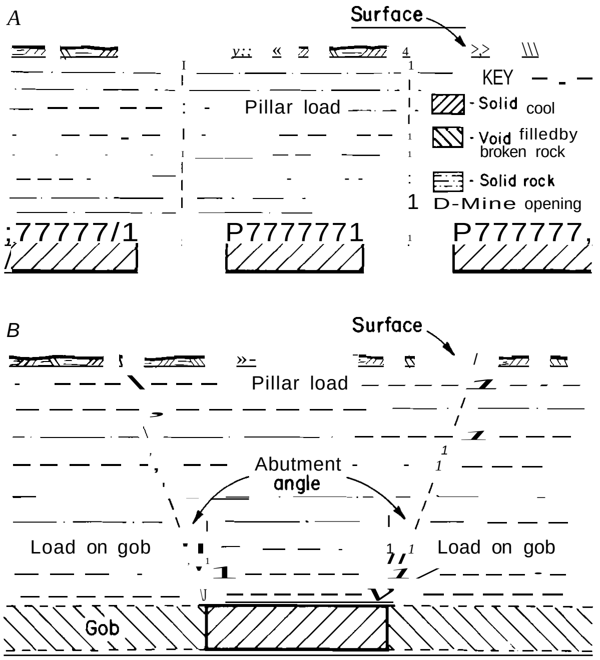


Figure 5. Estimation of pillar load.

Table 2. *Coal pillar strength formulas.*

Originator(s)*	Formula
Formula A - (Bieniawski)	Sp = S\ (0.36 + 0.64 [wlhD
Formula B - (Obert-Duvall/Wang)	Sp = S\ (0.22 + 0.78 [wlhD
Formula C - (Holland)	Sp = S\ *(Wlh)\f2*

·Original formulas are referenced in Bieniawski (1984)
S_p = Pillar strength, psi
S_1 = Unit coal strength (*in situ)* = 860 psi
w = pillar width, ft
h = pillar height, ft
psi = Ibs/in.^{2}

Pillar strength has been the subject of much research over the years. A number of formulas to predict pillar strength have been developed from laboratory tests, full-scale underground pillar tests, and practical mining experience (Bieniawski, 1984). Table 2 shows three of the most widely used empirically based formulas. Each of these formulas require that three parameters be known: a) the height of the pillar (normally the coalbed thickness); b) the width of the pillar; and c) the unit strength of the coalbed. The bed thickness and the pillar widths generally can be determined from mine maps and from geologic maps generated from borehole logs. Obtaining accurate determinations of the unit coal strength is more difficult because it normally requires testing of a large number of fresh coal samples. Experience has shown, however, that good approximations of the pillar strength can be obtained by using an average coalbed strength, which for Eastern coals is about 860 psi (4.9 MPa) (Mark, 1987).

Once the pillar load and the pillar strength have been calculated, a "safety factor" is determined by dividing the strength by the load. Safety factors in the range of 1.5 to 2.0 have been commonly accepted as safe for mining applications. Few mines require pillars to be stable for more than a few decades, however, so even higher safety factors should be considered necessary for permanent stability. Unfortunately, very little is known about the long term strength of coal pillars. Van Besien and Rockaway (1986) found that in 46 cases of subsidence attributable to pillar failure, the average time before the effect was observed on the surface was 36 yr after mining. It appears that pillars with safety factors in the range of 1.0 to 2.5 might be vulnerable to eventual collapse due to deteriorating ribs and creep of the core.

Mine Stability in the Sewell Coalbed

Mining of the Sewell Coalbed in the Maxwell Hill area was conducted in the late 1920's and early 1930's. The mine beneath most of Maxwell Hill is the Skelton Mine (Figure 6), with the Sprague Mine lying just to the south. The isopach map of the Sewell Coalbed (Figure 7) shows that the coal was about 4 ft (1.2 m) thick in the Maxwell Hill area.

Although complete and fully detailed maps of the Sewell Coalbed mines could not be obtained, it was possible to infer features of the mining methods from available maps. These maps show that room-and-pillar mining was practiced, with later extrac-

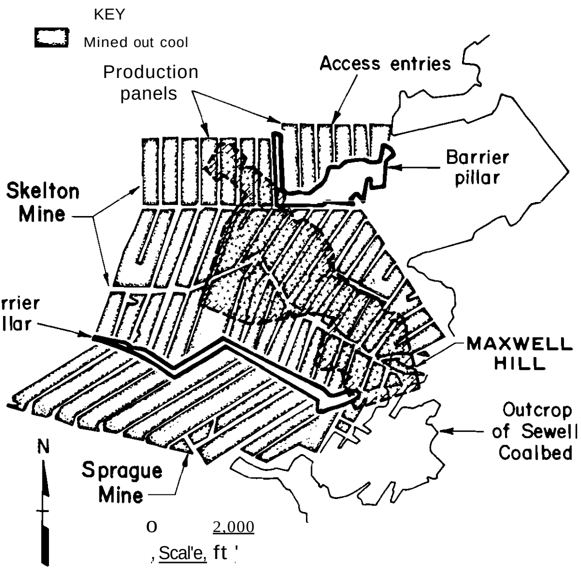


Figure 6. Abandoned mines in the Sewell Coalbed in the Maxwell Hill area.

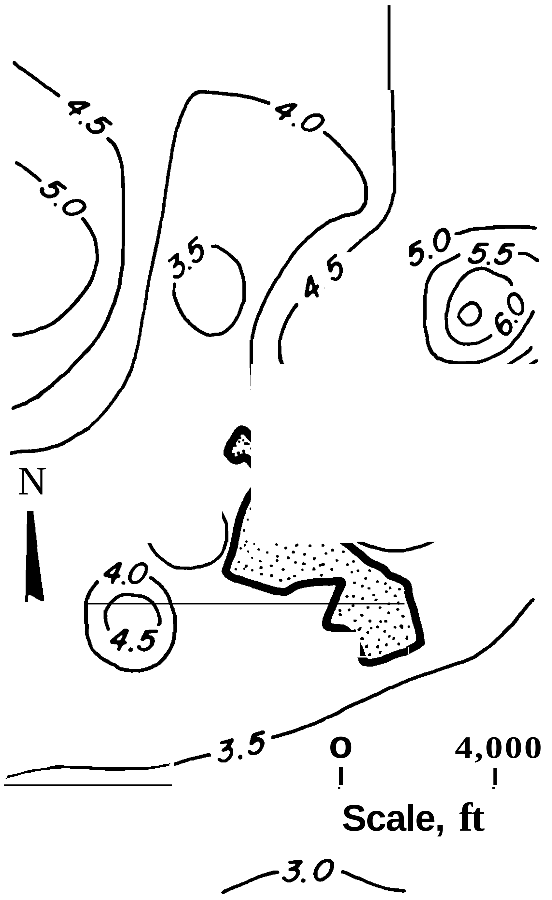


Figure 7. Sewell Coalbed thickness map; contour interval = 0.5 ft.

tion on retreat of the pillars. By the time mining was complete, nearly all of the coal had been removed in the production panels and even the access entries. In addition, the immediate roof above the Sewell Coalbed was observed to be relatively weak and prone to weathering. Above these large areas that were fully extracted, the roof must have collapsed almost immediately. Surface subsidence would have resulted. and all rock movement would have ceased many years ago.

The maps also show that a solid block or rib of coal, known as a barrier pillar, was left between the two mines. A second large barrier pillar was left north of Maxwell Hill in the Skelton Mine for an unknown reason. It appears likely that these are the only significant remaining mine structures in the Sewell Coalbed. The narrower of the two pillars, and thus the one most likely to fail, is the barrier between the Sprague and Skelton mines. The mine map shows that the minimum width of this pillar is 75 ft (23 m). The depth of cover above this pillar is obtained by subtracting the thickness of the interburden between the Sewell and Beckley Coalbeds (Figure 3) from the depth of cover for the Beckley Coalbed (Figure 2). Then the pillar load may be calculated by assuming that the pillar is bordered by two gob areas.

Observations of Sewell Coalbed outcrops indicate that the coal is probably of average strength. When the barrier pillar strength is calculated using the three formulas listed in Table 1, the resulting safety factors range between 2.5 and 4.2. The actual safety factors are probably even higher than these estimates, because the pillar strength formulas assume that a pillar is square, and underestimate the strength of long "strip" pillars like the barrier pillar. In conclusion, it appears unlikely that failure of the barrier pillar has occurred, or that the seismic disturbances relate to mining in the Sewell Coalbed.

Mine Stability in the Beckley Coalbed

The Beckley Coalbed was mined in the Maxwell Hill area about 30 years ago. The mine in the Beckley Coalbed was also called the Skelton Mine. Because the mining operation was more recent, a better map is available for it than was the case for the Sewell Coalbed. The mine map (Figure 8) indicates that the coal under the Maxwell Hill area was accessed by a set of main entries, oriented approximately N-S, and by two sets of submains, oriented E-W. Within these mains and submains the pillars were laid out on a regular pattern and were not extracted later. Panel entries were then driven off the mains and submains into two large blocks of reserves, where high-extraction mining was conducted. The mine plan in the production panels shows that 30 to 45 ft (9.1 to 13.7 m) wide rooms, approximately 250 ft (76.2 m) long, were driven between narrow production pillars perpendicular to the panel entries.

The mining method used in the Beckley Coalbed left at least six types of pillars of varying sizes in place when mining was completed. Within the mains and submains, the support or chain pillars were not extracted when the area was abandoned. Barrier pillars were also left adjacent to mains, submains and high-extraction areas. Even within the high extraction area, much coal was left in the form of panel pillars, production pillars, and irregular remnant pillars.

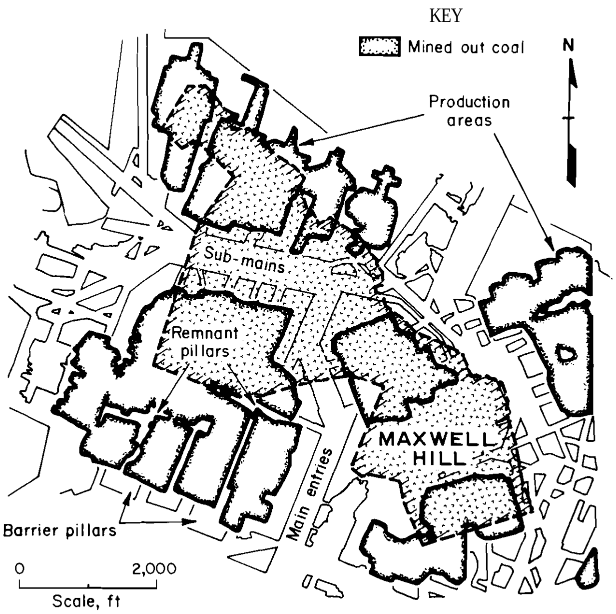


Figure 8. Abandoned mine in the Beckley Coalbed in the Maxwell Hill area.

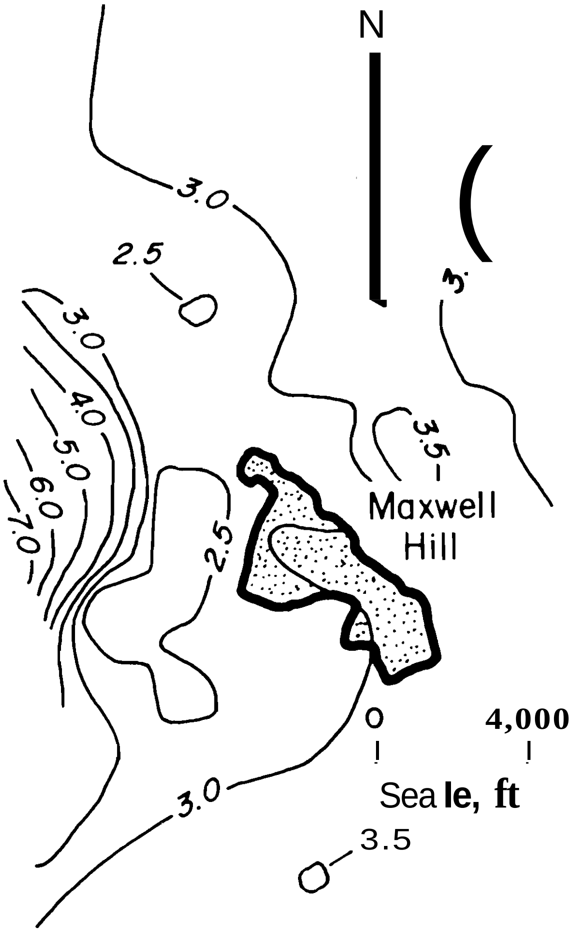


Figure 9. Beckley Coalbed thickness map; contour interval = 0.5 ft.

Table 3 gives the ranges in pillar widths, pillar lengths, and entry widths for each of the six pillar types. It also shows the safety factors calculated using the three pillar strength formulas. The coal thickness used in the calculations was 3.0 ft (0.9 m) (see Figure 9) with an average unit coal strength of 860 psi (4.9 MPa).

Several conclusions can be drawn from the data in Table 3. First, the safety factors calculated for the production room pillars are almost all less than 1.0, which suggests that many of them probably failed during or shortly after mining. The collapse of some of these pillars would have overloaded any adjacent pillars, so it seems highly unlikely that many of these production pillars could have survived for any length of time. Similarly, even though the safety factors calculated for the panel entry pillars are mostly greater than 1.0, the additional abutment

Table 3. *Results of the Beckley pillar analysis.*

		Pillar Strength					Safety Factors		
Pillar Type	Pillar Widths (ft)	Entry Widths (ft)	Pillar Load (ksi)	Formula A (ksi)	Formula B (ksi)	Formula C (ksi)	Formula A	Formula B	Formula C
Production Room	15-20	30-45	2.2-4.8	2.1-2.6	*1/6-1.9*	1.9-2.2	0.4-1.2	0.3-0.9	0.40-1.0
Panel Entry	22-26	22-26	1.8-2.4	2.8-3.2	2.1-2.3	2.3-2.5	1.1-1.8	0.8-1.3	0.9-1.4
Remnants	55-92		2.3-3.4	6.2-10	4.1-6.5	3.7-4.8	1.8-4.3	1.2-2.8	1.1-2.1
Submains	26	22-30	1.7-2.3	3.2	2.3	2.5	1.4-1.9	1.0-1.3	1.1-1.5
Mains	30-37	22-30	1.4-2.0	3.7-4.3	2.6-3.0	2.7-3.0	1.8-3.2	1.3-2.2	1.4-2.2
Barriers	150		1840	14	8.9	5.7	7.6	4.8	3.1

ksi = 1,000 lbs/in^2.

loading from the failure of the production pillars probably caused their failure.

The production room and panel entry pillars are not the only pillars in the high-extraction areas, however. Several remnant pillars of differing widths were left between production panels. When the abutment loads from the gob are considered (as they are in Table 3), the safety factors of several of these pillars are in the range of 1.0 to 2.5. Therefore, the present instability could be related to the failure of these remnant pillars.

Table 3 also suggests that failure of pillars in the mains and submains could be occurring at present. For both of these types of pillars, the calculated safety factors are within the 1.0 to 2.5 range, indicating short-term stability and long-term instability of pillars is possible. In addition, in room and pillar configurations, the initial failure of one pillar may cause other adjacent highly stressed pillars to fail (the "domino" effect). On the other hand, the safety factor calculated for even the smallest of barrier pillars (I50 ft or 45.7 m wide) is so high that eventual failure is highly unlikely.

The analysis indicates that the first condition for seismic disturbance, instability at the mine level, may very well exist in the Beckley seam under Maxwell Hill. The probable instability is most likely related to the failure of the pillars in the mains or submains, or the failure of remnant pillars in the production areas. In the following section, the existence of the second postulated condition necessary for seismic activity, the presence of appropriate strong and massive sandstone strata in the rock above the mine, is evaluated.

ROOF ROCK CHARACTERISTICS

Eariier it was stated that massive sandslOnes occur between the Beckley and Sewell Coalbeds. The following sections describe the properties of these sandstones in detail and discuss their capacity for contributing to the earth tremors in the Maxwell Hill area.

Geology of the Rock
Above the Beckley Coalbed

The geometry and areal extent of the rock units above the Beckley Coalbed were determined by examining and mapping 26 driller's logs from prior diamond coreholes around the Maxwell Hill area (Figure 10). An isopach map derived from these logs (Figure 10) indicates that 42 to 83 percent of the rock between the Beckley and Sewell coalbeds in the Maxwell Hill area is sandstone.

Stratigraphic analysis (Figure 1) shows the interval to consist of three distinct sandstone members (from top downward): the Upper Welsh Sandstone, the Upper Raleigh Sandstone, and the Lower Raleigh Sandstone. The Upper Welsh Sandstone is thin and mainly comprised of interbedded sandstone in this area, so we have not considered it further. The Upper Raleigh Sandstone is predominately a quartz arenite and is typically referred to as quartzite in drill logs. This designation highlights the extreme difficulty in penetrating this unit and reflects on its overall strength characteristics. The Lower Raleigh Sandstone is predominately a lithic arenite that is also very difficult to drill. A lithic arenite is similar to a quartz arenite except it is slightly finer grained and contains more metamorphic rock fragments.

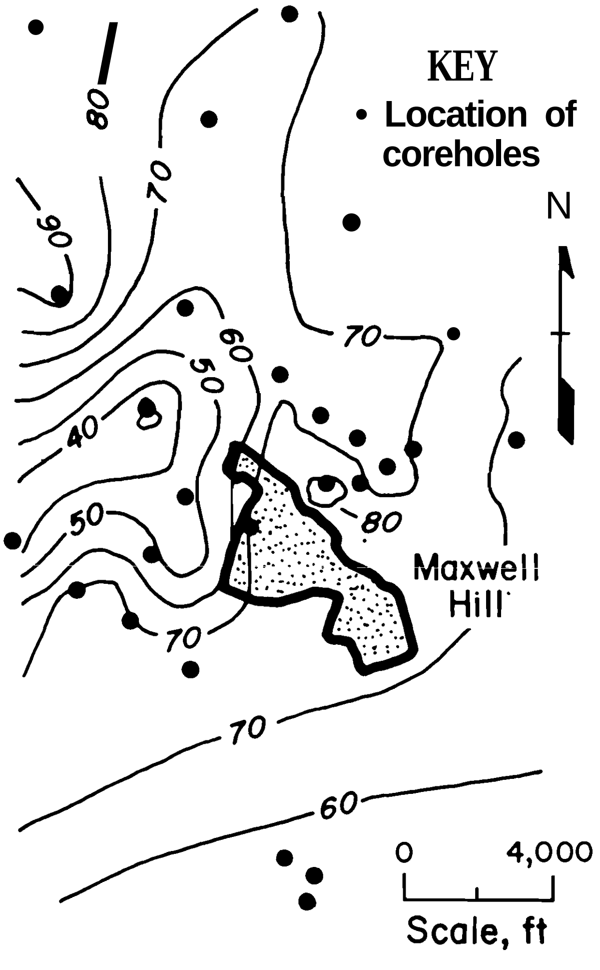


Figure 10. Percentage of sandstone between the Sewell and Beckley Coalbeds; contour interval = 10 percent.

Figure 11 is an isopach map of the Upper Raleigh Sandstone. Under Maxwell Hill the Upper Raleigh Sandstone ranges from 0 to as much as 100 ft (30.5 m) thick. Houseknecht (1980) described the internal structures of the Upper Raleigh Sandstone. The bottom contact with the underlying units, most commonly shales and siltstones but in some areas the Lower Raleigh Sandstone itself, is extremely sharp. Above this contact, the sandstone contains both trough and tabular crossbeds and local lenses of shale and coal. The *en echelon* bedding plane discontinuities are 2 to 10 in. (5 to 25 cm) apart and extend laterally tens of feet through the sandstone body.

The thickness of the Lower Raleigh Sandstone in the Maxwell Hill area (Figure 12) ranges between 50 and 90 ft (15.2 to 27.4 m). The Lower Raleigh Sandstone was observed in nearby outcrops to possess the following internal structures:

1. The bottom contact with the underlying shale and siltstone units is sharp.
2. Above the contact, the sandstone contains large trough crossbeds generally 30 to 60 ft wide (9.1 to 18.3 m), and less than 6 ft (1.6 m) thick, but at least one 15 ft (4.6 m) thick intact block was observed.
3. Above the lower 10 to 20 ft (3 to 6.1 m) of this sandstone, the bedding planes are more tabular and are commonly 8 to 24 in. (20.3 to 70 cm) thick. This unit was extremely difficult to break with a hammer at the outcrop.

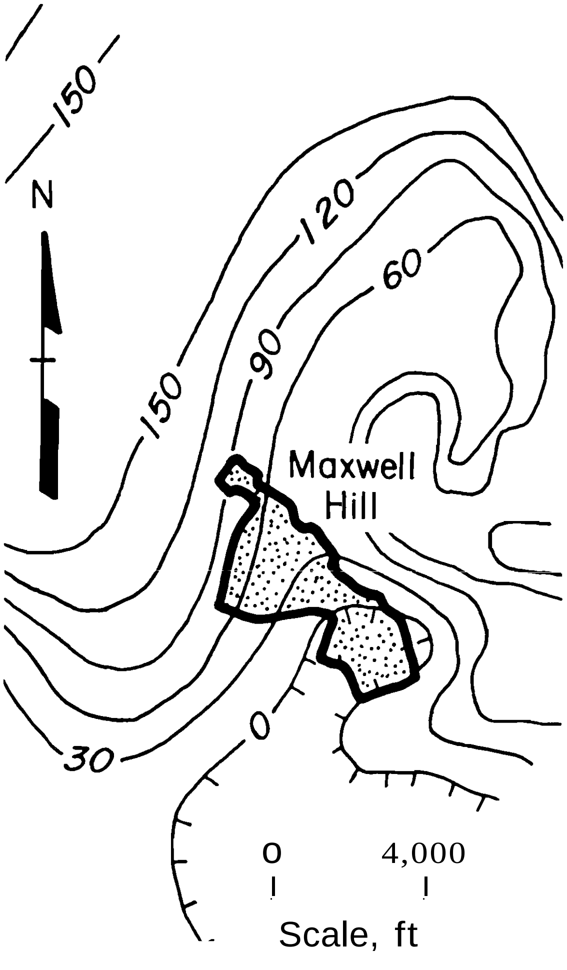


Figure 11. Regional thickness of the Upper Raleigh Sandstone; contour interval = 30 ft.

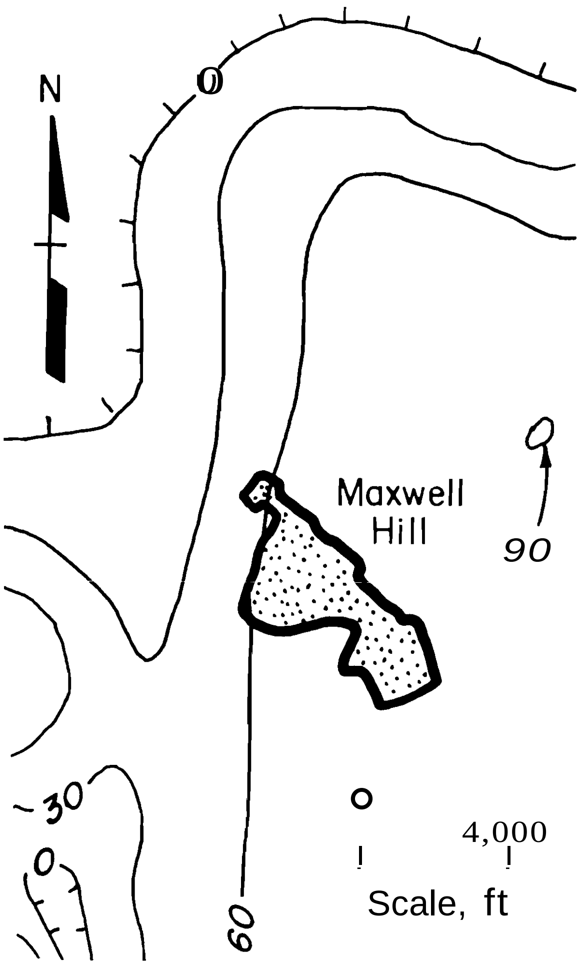


Figure 12. Regional thickness of the Lower Raleigh Sandstone; contour interval = 30 ft.

Physical Properties of the Massive Sandstone Roof

Only two rock samples were collected for physical property testing to qualify and quantify the relative strength of the Lower and Upper Raleigh Sandstones. One sample came from an exposure of strata found above the reclaimed portal area of the Skelton Mine along Cranberry Creek. At this location a large sample of the Upper Raleigh Sandstone was broken off the outcrop. In addition to this sample, an NX size core was obtained from the Lower Raleigh Sandstone from the roof of a mine located approximately 10 m north of Maxwell Hill. Both samples were tested at the Bureau's rock mechanics laboratory at the Pittsburgh Research Center.

The laboratory test results are summarized in Table 4. These results show extremely high compressive strengths for coal measure rocks. Typical sandstones in the northern Appalachian Coal Fields have compressive strengths ranging from 6,000 to 20,000 psi (41.4 to 137.9 Mpa). Values for the modulus of elasticity range from 4.6 to 8.7 x 10^6 psi (31.7 to 60 GPa), which indicates that the sandstones are extremely stiff. Poisson's ratios for the samples ranged from 0.12 to 0.36. The relatively high strengths of the Raleigh Sandstones (28,000 to 33,000 psi or 193.1 to 227.6 Mpa) match strengths reported for other massive sandstones in the southern Appalachian Coal Basin (Iannacchione et aI., 1987). The presence of several stiff sandstone members in the extensively undermined regions of southern West Virginia, southwestern Virginia and eastern Kentucky suggests a potential for additional abandoned mine seismicity.

POTENTIAL MAGNITUDE OF SEISMIC EVENTS

Both conditions of the stated hypothesis for mining-induced seismicity are present beneath Maxwell Hill. This section estimates the potential magnitude of the seismic events that could occur as a result of mine instability. The first step is to estimate the amount of energy that might be released in a single failure event.

The most probable source of the seismic energy is the strain energy stored within the sandstone roof. Strain energy develops within an elastic solid when it is deformed by applied forces. The amount of strain energy stored per unit volume of rock may be estimated by the following equation (Duvall and Stephenson, 1965):

$$W_o = (1/2E)(\sigma_1^2 + \sigma_2^2 + \sigma_3^2) - (\mu/E)(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3) \qquad \text{Eq. 1}$$

where:

W_o = strain energy per unit volume
E = modulus of elasticity
μ = Poisson's ratio
$\sigma_1\ \sigma_2\ \sigma_3$ = principal stresses.

Knowledge of the principal stresses is necessary to use Equation 1 for estimate the strain energy that could be stored in the Raleigh sandstones. The *in situ* field stresses can be used to approximate the principal stresses. The vertical field stress was estimated at 660 psi (4.6 MPa) based on the depth of cover. The

Table 4. *Physical properties test.*

	Skelton Portal	Bonnie Mine
Uniaxial Compressive Strength	32,670 + psi[1]	27,950 psi
Modulus of Elasticity	4.65 x 10^6 psi[2] 7.28 x 10^6 psi[3]	5.7 x 10^6 psi[2] 8.7 x 10^6 psi[5]
Poisson's Ratio		

[1] Sample did note fail, exceeded load frame capabilities.
[2] Secant Modulus at 20,000 psi.
[3] Tangent Modulus at 20,000 psi.
[4] Secant value.
[5] Tangent value.

horizontal field stresses in the roof above several Beckley coalbed mines were measured by Agapito and others (1980). The maximum horizontal stress for these coal mines averaged 3,285 psi (22.7 MPa) and the minimum 2,420 psi (16.7 MPa). Based on the test results reported in the previous section, representative values for the modulus of elasticity and Poisson's ratio for the sandstone can be taken as 6,000,000 psi (41.4 GPa) and 0.24, respectively. These values indicate that the strain energy stored in the sandstone is about 150 foot-lbs/ft^3 (7,182 Joules/m^3).

Progressive failure of the pillars beneath the sandstone would result in a greater and greater roof span. Because the strength of the strata determines its maximum span, stronger roof will bridge greater areas. When the strength of the roof is exceeded, it fails either by fracturing, by slipping along a preexisting joint surface, or by collapse. In any case a volume of rock is suddenly destressed, resulting in the release of the stored strain energy. An estimate of the total volume of rock destressed in a single failure event can therefore be used to estimate the total energy available for seismicity.

The very stiff, massive sandstone can support relatively large spans before failure occurs. The largest potential single failure would be of a block as wide and as long as the distance across the main entries and as thick as one entire sandstone unit. Such a block would measure about 350 x 350 x 90 ft (106.7 x 106.7 x 27.4 m), and would release 1.7 x 10^9 foot-lbs (2.3 x 10^9 Joules) of strain energy. A more typical span for very strong roof, as observed in longwall mines, is closer to 40 ft (12.2 m) (de Bakker et al., 1979). The failure of a 40 x 40 ft (12.2 x 12.2 m) span in a 6 ft (1.8 m) thick bed would release 1.5 x 10^6 foot-lbs (2 x 10^6 Joules) of energy.

Not all of the stored strain energy, normally released in the form of elastic vibrations, produces seismicity. Ortlepp (1983) estimated that as little as 5 percent of the total amount of energy released by rock failure takes the form of seismic vibrations. Much higher percentages may be achieved when rock fails in rupture. Therefore, the range of seismic efficiency for mine induced events could be between 5 and 100 percent of the total energy released.

Estimates of the energy involved in a seismic event may be converted to the familiar Richter scale by the following equation (Richter, 1956):

$$10glo(E) = 12 + 1.8\ M \qquad \text{Eq. 2}$$

where:

E = energy (dyne-cm)
(Note: 1 foot-lb = 1.356 x 10^7 dyne-cm)
M = Richter magnitude.

Table 5 gives the approximate Richter magnitudes that would be associated with the failure events described above. If 5 percent of the available strain energy of a rock block measuring 350 x 350 x 90 ft (106.7 x 106.7 x 27.4 m) is released as seismic energy, the event could produce a Richter magnitude of M = 1.7. If all of the available strain energy of the rock block is released as seismic energy, the event could produce a Richter magnitude of M = 2.4. A similar calculation assuming the failure of a 40 x 40 x 6 ft (12.2 x 12.2 x 1.8 m) block results in a range of Richter magnitudes between M = 0.0 and 0.7.

None of the vibration events in the Maxwell Hill area were strong enough to be picked up by the Virginia Polytechnic Institute's (VPI) Seismological Observatory located in Blacksburg, Virginia (Chapman, 1988). Bollinger and others (1986) determined the theoretical detection and location capabilities of VPI's Seismological Observatory; and an event occurring in the Beckley area would probably have to be of at least Richter magnitude M = 1.8 to register on the Observatory's instruments. This information suggests that the actual magnitudes of the events experienced at Maxwell Hill were less than 2.0. However, Long and Copeland (1989) reported seismic events associated with a coal mine strata collapse had stronger surface waves than expected from a M = 3.6 earthquake event. They theorized that the mine-induced event generated lower frequency body waves which probably excited the development of the more destructive surface waves. Perhaps the Maxwell Hill events were dominated by lower frequency waves, causing a stronger local intensity than would be expected from typical earthquakes of similar Richter Magnitudes.

Table 5. *Theoretical Richter magnitudes of possible mining-related events near Maxwell Hill.*

Block Size (ft)	Percent of Total Energy Released as Seismicity	Richter Magnitude
350x350x90	5	1.7
	100	*2A*
40 x 40 x 6	5	0.0
	100	0.7

The final step in the analysis is to determine what effect events of this magnitude could have on the surface. As mentioned earlier, the descriptions of the earth tremors reported by Maxwell Hill residents (Table I), indicates the largest of these events was about $I_a = IV$. According to the Modified Mercalli scale, the threshold for even minor structural damage is an I_a of VI.

Sibol and others (1987) studied the relationship between Modified Mercalli intensity and the Richter magnitude for North American earthquakes. Their data indicate that the range of Richter magnitudes responsible for Modified Mercalli intensity equal to IV is approximately M = 1.7 to 4.4. The events postulated for Maxwell Hill are at the low end of this range. The most likely explanation is that Sibol and others' (1987) data cover natural earthquake events, whose source is typically several miles below the earth's surface. The sources of mine-related events are much shallower, only several hundred feet in the case of Maxwell Hill. Seismic waves attenuate (diminish) in amplitude from the source by the square-root of the distance. Therefore, a shallower event locally feels as strong as a deeper event of greater magnitude, because the vibrations are focused on the area immediately above the focal center. On the other hand, seismic energy might be expected to dissipate as it passes through fractured ground, such as probably exists at the level of the abandoned mines in the Sewell Coalbed.

The data presented by Sibol and others (1987) also indicate that the smallest recorded event resulting in an $I_a = VI$ (the structural damage threshold) was of $M = 2.0$. The typical range of $1_0 = VI$ events is M = 2.8 to 4.7. Therefore, even though they are near surface, postulated seismic events associated with abandoned mine collapse in the Maxwell Hill area probably would cause no significant damage on the surface.

The analysis presented here is based on the assumption that relatively large volumes of roof rock suddenly fail and become destressed. Only a limited amount of abandoned mine roof beneath the Maxwell Hill area may be subject to such failure. Therefore, if the postulated process is causing the seismic events, they should be of finite duration and may, in fact, be completed.

SUMMARY AND CONCLUSIONS

In summary, the earth tremors experienced by residents of Maxwell Hill could possibly be caused by subsurface movements related to abandoned mines. The most likely location of mine-level instability is the Beckley Coalbed, where numerous support pillars were left in place when mining was completed. Many of these pillars were evaluated as having insufficient strength to insure long-term stability. Failure of pillars would create additional stresses on the mine roof. Geologic evaluation indicates that the roof above the Beckley Coalbed contains two strong, massive sandstone units. These units have the potential to store large quantities of strain energy, which could be released suddenly if the roof became overstressed, causing vibrations on the surface above.

Based upon this data, three significant conclusions are apparent. First, the analysis indicates that no damage to surface structures in Maxwell Hill is likely to result from the postulated mining-induced seismic events, and that the events will likely be of finite duration. Second, the conditions present in the Maxwell Hill area, full extraction mining beneath massive sandstone units, are common in other locations within the southern Appalachian Coal Basin. It seems probable that events similar to those which occurred at Maxwell Hill may develop in this region in the future. Even if damage does not occur, the nuisance to local residence can represent a considerable environmental issue, especially as more residential communities are established over abandoned mines. Finally, the analysis of the events in Maxwell Hill support observations by previous researchers that mining-induced seismicity produce locally greater felt intensities than might be predicted from their estimated Richter magnitudes. Clearly, more qualitative research is needed to assess the potential danger associated with mining-induced seismicity.

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