A Guide to Surface Features Related to Underground Coal Mining

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Executive Summary

The purpose of this guide is to assist investigators conducting geologic hazard assessments with the understanding, detection, and characterization of surface features related to subsidence from underground coal mining. Subsidence related to underground coal mining can present serious problems to new and/or existing infrastructure, utilities, and facilities. For example, heavy equipment driving over the ground surface during construction processes may punch into voids created by sinkholes or cracks, resulting in injury to persons and property. Abandoned underground mines also may be full of water, and if punctured, can flood nearby areas. Furthermore, the integrity of rigid structures such as buildings, dams and bridges may be compromised if mining subsidence results in differential movement at the ground surface. Subsidence of the ground surface is a phenomenon associated with the removal of material at depth, and may occur coincident with mining, gradually over time, or sometimes suddenly, long after mining operations have ceased (Gray and Bruhn, 1984). The spatial limits of underground coal mines may extend for great distances beyond the surface operations of a mine, in some cases more than 10 miles for an individual mine. When conducting geologic hazard assessments, several remote investigation methods can be used to observe surface features related to underground mining subsidence. LiDAR-derived DEMs are generally the most useful method available for identifying these features because the bare earth surface can be viewed. However, due to limitations in the availability of LiDAR data, other methods often need to be considered when investigating surface features related to underground coal mining subsidence, such as Google Earth and aerial imagery. Mine maps, when available, can be viewed in tandem with these datasets, potentially improving the confidence of any possible mining subsidence-related features observed remotely. However, maps for both active and abandoned mines may be incomplete or unavailable. Therefore, it is important to be able to recognize possible surface features related to underground mining subsidence. This guide provides examples of surface subsidence features related to the two principal underground coal mining methods used in the United States: longwall mining and room and pillar mining. The depth and type of mining, geologic conditions, hydrologic conditions, and time are all factors that may influence the type of features that manifest at the surface. This guide provides investigators a basic understanding about the size, character and conditions of various surface features that occur as a result of underground mining subsidence.

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1 Introduction

Underground mining of coal may result in ground subsidence that can manifest as many different features at the surface, such as cracks, sinkholes, and large depressed areas known as subsidence basins. Subsidence of the ground surface is a phenomenon associated with the removal of material at depth, and may occur coincident with mining, gradually, over time, or sometimes suddenly, long after mining operations have ceased (Gray and Bruhn, 1984). The spatial limits of underground coal mines may extend for great distances beyond the surface operations of a mine, often crossing under buildings, roadways, utilities, and streams. When mining-related subsidence occurs at the surface, buildings, infrastructure, and agricultural land may be damaged (Mining Subsidence Engineering Consultants, 2007), and stream loss and disturbance (Peng, 2006, and Kay et al., 2006) may occur. Being able to identify and characterize the potential hazards associated with mining subsidence is of utmost importance when constructing new infrastructure and buildings through areas that cross underground mines. Mining subsidence-related geologic hazard assessments for existing or proposed facilities and/or infrastructure are typically conducted by performing an initial desktop review using remote sensing techniques. Features identified during the initial remote sensing review are often later field-verified and characterized. The purpose of this technical report is to assist in the understanding, detection, and characterization of surface features related to subsidence from underground coal mining when conducting these assessments.

Subsidence is a time-dependent readjustment of the strata above a mine (Gray and Bruhn, 1984), and if geologic conditions permit, features related to this readjustment may manifest at the surface. Vertical movements commonly associated with mining-related ground subsidence are typically the greatest, though horizontal movements also occur (Gray and Bruhn, 1984), sometimes with magnitudes at least as great as the vertical movements (Hebblewhite, 2001). Typical surface movements associated with underground coal mining may extend over areas from a few square feet to many acres, and vertically from inches to several feet (Gray and Bruhn, 1984). In extreme cases, horizontal movements as much as 1 inch (25mm) have occurred at a distance of 1 mile (1.5 kilometers) from underground coal mining (Reid, 1998).

The findings presented in this report are primarily based on a literature review and information obtained by consulting with mining subsidence experts. This report provides examples of surface features related to two of the most common forms of underground coal mining in the United States: longwall mining and room and pillar mining. When available, site-specific examples of surface features related to underground coal mining subsidence are included. Furthermore, this report focuses on subsidence features related to generally flat-lying coal seams, though consideration is also given to flat-lying coal seams in sloping terrain. This report does not include information about surface subsidence features related to mining inclined coal seams.

2 Investigation Methods

When performing mining-related geologic hazard assessments a common remote sensing method is to review digital elevation models (DEMs) derived from Light Detection and Ranging (LiDAR). These LiDAR-derived DEMs are useful for identifying surface features related to mining subsidence because the vegetation signal can be removed during data processing, resulting in a computer-generated model of the bare earth surface. This report provides several examples of surface features observed from LiDAR, though LiDAR imagery is not included for every feature type due to a lack of readily available data.

While LiDAR is often the preferred tool when performing remote sensing reviews for mining-related surface subsidence, data coverage is not always available. When LiDAR coverage is not available, typically either Google Earth satellite imagery or aerial photography is used for investigating surface features. One advantage to using these alternate methods is that historic imagery is often available and data are typically readily accessible within the public domain. However, one disadvantage is that vegetation cover may completely obscure mining-related surface features.

Another useful means for identifying possible areas of mining-related surface subsidence is to review mine maps provided by public agencies or mining companies. Mine maps can be geospatially referenced and viewed in tandem with LiDAR and/or aerial imagery using a geographic information system such as Arc Map (Figure 1). Geospatially referenced mine maps enable investigators to locate possible subsidence-prone areas, such as areas between coal pillars or mine entry points. However, mine maps may not show the final condition of a mine, may be unavailable, or may have never been created.

Field investigations may be conducted if an area is known to cross the location of an underground mine, or if surface features observed remotely suggest the presence of underground mining. When available, images of surface features related to underground coal mining subsidence are provided in this report. It should be noted that mine entrances (portals), piles of waste rock (slag heaps), and air shafts are some of the surface features that may help identify the location of underground mines. However, this report addresses only subsidence-related surface features and therefore, these other mining features have been omitted from this report.

3 Mining Techniques

This section describes the two principal underground mining techniques implemented in the United States today: room and pillar mining and longwall mining. Mining type is important with regard to subsidence because different surface features result from each of these two mining techniques. Subsidence related to room and pillar mining is not a planned occurrence, and may occur without warning, often long after mining is complete. In contrast, with longwall mining, subsidence is expected to occur as part of the mining process.

3.1 Room and Pillar Mining Methods

Room and pillar mining is a technique of underground coal mining that leaves pillars of coal unmined to prevent roof collapse (Figure 2). In the 18th and 19th centuries, underground mining of coal occurred as small hand-operations at shallow depths, and pillars of coal were left as a matter of convenience and safety for miners (Gray and Bruhn, 1984). Early room and pillar mining was conducted in the eastern United States with overburden depths sometimes less than 25 feet (Gray and Bruhn, 1984). Early room and pillar mining techniques resulted in extraction ratios (i.e., the ratio of coal removed to what remains) of about 30-40%, in comparison to modern extraction ratios, of about 55-65% (Gray and Bruhn, 1984). Modern room and pillar mining uses a continuous miner machine, which is able to remove large quantities of coal with the use of a cylindrical-shaped cutting head (Bise, 2013).

For room and pillar mining, virtually no subsidence is observed at the time of mining. Subsidence may occur suddenly, often long after mining operations are complete (Gray and Bruhn, 1984). Subsidence from room and pillar mining typically results from pillars weakening and eventually collapsing or punching into the floor (Gray and Bruhn, 1984) or through the development of sinkholes (discussed in section 6.1.1). In some cases mining-related surface subsidence occurred hundreds of years after mining was completed (Gray and Bruhn, 1984).

In the late 19th century, pillar recovery mining was implemented to achieve greater production of coal from mines in order to provide fuel for the steel industry (Gray and Bruhn, 1984). In this method of coal removal, the long, narrow pillars that were left between the rooms are removed in a second stage of mining (Gray and Bruhn, 1984). Pillar recovery mining is accomplished using a continuous miner machine to remove coal, while mobile roof supports keep the roof from collapsing (Bise, 2013). As pillars are removed, the roof is then systematically allowed to collapse to the floor (Gray and Bruhn, 1984). This method of coal removal typically results in coal extraction ratios of about 80-90% (Cassidy, 1973).

3.2 Longwall Mining Methods

Longwall mining is one of the principal coal extraction methods used in the United States and involves the complete removal of large, rectangular panels (known as longwall panels) of coal (EIA, 1995). Passageways are dug around longwall panels on four sides using modern room and pillar mining techniques (Bise, 2013; EIA, 1995) (Figure 3). Longwall panels are then removed by mining on retreat, meaning that the panels are mined from the far end of the panel toward the entrance of the mine (EIA, 1995). In the 1970's, European longwall mining techniques were implemented in a northern West Virginia coal mine, which used mobile hydraulic roof supports to hold up the roof of the mine (Figure 4; Peng, 2006). As mining progresses toward the entrance of the mine the hydraulic roof supports move forward, protecting both the coal extraction equipment and personnel. However, as mining progresses forward, the roof immediately above the mined out area collapses, resulting in subsidence that transmits to the ground surface.

For longwall mining, surface subsidence occurs nearly concurrent with extraction. Surface subsidence has been observed to be about 90% complete when the location of the mining face (i.e., where coal extraction is taking place) is 0.75H to 1.0H beyond a given monitoring point at the surface, where H is the depth of the coal seam below the surface (Gray and Bruhn, 1984). Residual movements related to longwall mining are typically complete within two years after mining has occurred (Gray and Bruhn, 1984).

The dimensions of modern longwall panels in the United States range between about 600 to 1450 feet (180 to 440 meters) wide and 3000 to 16,000 feet (900 to 4900 meters) long (Peng, 2006). The most common longwall panel dimensions in the United States are about 1000 feet (300 meters) wide by about 8200 to 13,000 feet (2500 to 4000 meters) long. Height of material removed is usually about 4 feet (1.2 meters) for longwall mining systems using plows and 5 to 8 feet (1.5 to 2.4 meters) for longwall mining systems using shearers (Peng, 2006). Height of material removed is generally the seam height, but roof material is also extracted in many cases to make room for equipment and personnel (Peng, 2006). Longwall mining is conducted at depths on the order of hundreds of feet to greater than 1000 feet (300 meters) below the ground surface. Multiple longwall panels are commonly mined parallel to one another separated by chain pillars that are mined using modern room and pillar mining techniques (Figure 3).

4 Parameters Related to Subsidence Basins

This section describes fundamental parameters associated with surface movements in subsidence basins (see section 6.2.1 for a description of subsidence basins; also see Figure 5), including: vertical and horizontal movements, tilt, and curvature. This section also considers how the ground surface is affected by the width of the material removed and the position of the removed material relative to the surface. Because subsidence features at the surface are related to the collapse of strata at depth, it is important to understand how movements are transmitted to the surface. Thus, observations of overburden movements during longwall mining are also provided.

4.1 Vertical Displacement

Vertical movements are commonly associated with underground coal mining as a result of material collapsing into mined-out areas. As material collapses, the downward movement of overlying strata may propagate through the overburden, resulting in vertical displacements at the surface. In a subsidence basin, the maximum vertical displacement occurs at the center of the basin (Figure 5). Damage to infrastructure and buildings are typically a result of differential movements, rather than the absolute magnitude of the displacement (Gray and Bruhn, 1984).

4.2 Horizontal Displacement

Horizontal displacements at the ground surface are associated with either tensile (positive) or compressive (negative) strains. The edges of subsidence basins experience tensile strains, while the interior of the extracted area experiences compression (Gray and Bruhn, 1984). Similar to vertical displacements, surface structures and infrastructure are damaged as a result of differential displacement (Gray and Bruhn, 1984).

4.3 Tilting

Tilt is the result of differential movements within a subsidence basin and is defined as the change in vertical distance between two points divided by the linear distance between those points (Mine Subsidence Engineering Consultants, 2007). The first derivative of the subsidence profile therefore defines the tilt (Mine Subsidence Engineering Consultants, 2007). Tilt can be either positive or negative, though positive tilt is conventionally taken to indicate that the ground is increasing in subsidence in the direction of the measurement, i.e., towards the center of a subsidence basin (Mine Subsidence Engineering Consultants, 2007). Maximum tilt usually occurs at the inflection point of a subsidence profile (Mine Subsidence Engineering Consultants, 2007).

4.4 Curvature

Curvature is calculated as the change in tilt between two adjacent sections of the subsidence profile divided by the average length of those sections (Mine Subsidence Engineering Consultants, 2007). In idealized scenarios involving flat-lying terrain, curvature is typically understood to be convex over the edge of extracted areas and concave in the center of subsidence basins (Mine Subsidence Engineering Consultants, 2007). Surface structures located in areas of subsidence basins that have maximum curvatures and strain are generally the most impacted (Mine Subsidence Engineering Consultants, 2007).

4.5 Conceptualized Subsidence Profile in Flat-Lying Terrain

Figure 5 illustrates typical subsidence parameters for a subsidence basin (Holla and Barclay, 2000). The primary surface subsidence parameters include maximum subsidence (Smax), maximum ground tilt (Gmax), maximum compressive and tensile ground strains, and minimum radius of ground curvature (Figure 5). Extracted seam thickness, depth of cover, width of material removed, and the type of material in the goaf all determine the magnitude of subsidence (Figure 5). Gmax occurs where subsidence is roughly equal to one half Smax (Parsons and Brinckerhoff, 2007). Compressive and tensile strains occur as a result of horizontal movements, and are reported as the change in length of the ground surface per unit of the original length of the ground surface (Parsons and Brinckerhoff, 2007). Compressive strains typically occur above areas of extraction, whereas tensile strains typically occur above the goaf edges (Parsons and Brinckerhoff, 2007; Figure 5.)

4.6 Critical, Subcritical, and Supercritical Panel Widths

Maximum subsidence occurs when the extracted area of a given longwall panel reaches a critical width (Gray et. al, 1974; Figure 6). Removal of coal less than the critical width results in a subcritical condition where maximum subsidence will not be achieved (Figure 6), but smaller amounts of subsidence may occur. Conversely, if the critical width of a panel is exceeded the panel width is referred to as supercritical, and results in a subsidence basin, with expansive areas reaching maximum subsidence (Figure 6).

4.7 Overburden Movement Related to Longwall Mining

Peng (2006) describes overburden movement related to longwall mining as occurring in four zones within the stratigraphic column, including: (1) the caving zone, (2) the fractured zone, (3) the continuous deformation zone, and (4) the soil zone (Figure 7).

The caving zone refers to the area immediately above the removed coal, before the area caves into the void created by coal extraction (Peng, 2006). The caving zone ranges in thickness from 2 to 8 times the thickness of material removed (Peng, 2006).

The fractured zone is located above the caving zone and is an area where strata are broken into blocks by vertical, subvertical, and horizontal fractures (Peng, 2006). The thickness of the fractured zone ranges from 28 to 52 times the mining height; the combined thickness of the fractured zone and caved zone is between 30 to 60 times the mining height (Dahl and Von Schonfeldt, 1976).

The continuous deformation zone is located between the fractured zone and the soil zone (Peng, 2006). In this zone, the strata behave as an intact medium and do not form discontinuities in the rock mass like the fractured zone (Peng, 2006), but can deform to produce subsidence in the landscape above.

At the surface, the soil zone varies in thickness depending on many factors, such as topographic location, weathering processes, and bedrock geology. Surface features related to underground mining subsidence manifest in the soil zone. In general, cracks tend to open and heal in the center of the longwall panels and remain open permanently along the panel edges (Peng, 2006).

4.8 Angle of Draw

The angle of draw is defined as the angle from vertical of a line connecting the edge of the extracted area at depth and the lateral limit of subsidence at the surface (Figure 6). The lateral limit of surface subsidence for subsidence basins is defined as the contour line of 0.4 inches (10mm) of subsidence (Lou and Peng, 1997). Angles of draw in Europe have been observed to vary between 19 to 45 degrees (Gray and Bruhn, 1984). In the United States, angles of draw are generally between 20 to 28 degrees with some locations observed as high as 35 degrees (Gray and Bruhn, 1984). The West Virginia Department of Environmental Protection (WVDEP) uses a value of 30 degrees for the angle of draw when assessing the potential effects of subsidence in pre-longwall mining surveys (personal communication, Steve Ball, Geologist, WVDEP, 2013). Typically, large angles of draw are associated with unconsolidated deposits and small angles of draw are associated with consolidated deposits (Zwartendyk, 1971).

4.9 Width to Depth Ratio

The width to depth ratio is defined as the width of the extracted area divided by the depth of the coal seam below the surface. When a critical width to depth ratio is achieved, maximum subsidence will occur at the surface. It follows that as depth increases, so to must the width of longwall panels in order for maximum subsidence to occur at the surface (Gray and Bruhn, 1984). Maximum subsidence for sandstone typically occurs near width to depth ratios of 1.0, whereas for interbedded shales and siltstones maximum subsidence occurs near width to depth ratios of 1.4 (Gray and Bruhn, 1984). In the United States, the maximum subsidence observed at the surface is slightly greater than 70% of the extracted material, and this value is only achieved when the critical width to depth ratio is reached (Gray and Bruhn, 1984).

5 Subsidence in Sloping Terrain

Some researchers have documented that surface topography has no influence on the amount of vertical subsidence that occurs (Kohli et al., 1980 in Gray and Bruhn, 1984; Khair et al., 1988), while others have reported that net "upsidence," or movements in the "up" direction, can occur as a result of extreme compressive forces in topographic lows (Kay et al., 2006). Others have reported that in rugged terrain, maximum subsidence is greatest at ridge tops and the least in valley lows, based on movement associated with the valley sides (Holla and Barclay, 2000; Ewy and Hood, 1983).

Geotechnical models predict extensive tensile strains along the upslope side of subsidence basins (discussed in section 6.2.1) in addition to local ground steepening. Whittaker and Reddish (1989) report that geotechnical models using either a (1) stochastic model influence function or (2) a graphical projection procedure coupled with empirical data (National Coal Board, 1975) to predict surface subsidence result in similar subsidence profiles (Figure 8). For either model, the upslope side of the subsidence basin experiences an increase in the zone of tension at the surface (Whittaker and Reddish, 1989). Tensile strains on the upslope side of the subsidence basin may result in both local steepening and fractures at the surface (Whittaker and Reddish, 1989). Similarly, the downslope side of the subsidence basin experiences tensile strain. However, the general trend for the downslope side of the subsidence basin is toward increased slope stability as a result of decreases in local slope angle (Whittaker and Reddish, 1989). The center of the subsidence basin experiences compressive strain, the magnitude of which increases as overall slope angle increases (Whittaker and Reddish, 1989). As surface slopes increase, the zone affected by tensile strain increases on the upslope side of the subsidence basin, but maximum tensile strains decrease. Conversely, for increasingly steeper slopes, tensile strains increase at the downslope side of the subsidence basin, yet the area of the zone affected decreases (Whittaker and Reddish, 1989).

A study conducted by Khair (1988) investigating longwall mining in northern West Virginia showed that topography has a significant effect on the degree of horizontal movement at the surface. The most obvious effect of topography on horizontal movements was found to occur along the centerline of a longwall panel, and typically resulted in movement parallel to the fall line (Khair et al., 1988). The magnitude of horizontal movement was found to be related to the slope and slope direction relative the longwall panel, with steep hills that face the direction of mining resulting in the largest amount of displacement (Khair et al., 1988). Khair et al. (1988) found geomorphic evidence for surface subsidence in the form of (1) tension cracks that ranged from 1 inch to 3 feet (25mm to .9 meters) wide, (2) turf rolls (where grass/sod rolls up on itself), (3) push-outs (similar to turf rolls but occurring in areas without ground vegetation), and (4) heaving at the base of slopes (due to horizontal compression).

6 Geomorphic Features Related to Subsidence

The purpose of this section is to provide descriptions and examples of the various types of mining-related subsidence features that may occur from underground coal mining. This section divides geomorphic features based on those that occur as a result of (6.1) room and pillar mining, (6.2) longwall mining and pillar recovery mining, or (6.3) from either type of mining. With the exception of the example of the linear sinks (6.3.3), all of the features in this section have been documented in peer-reviewed literature relevant to mining subsidence. Images are included for most of the subsidence features in this section, though no remote imagery showing rockfall (6.2.2), landslides (6.2.2) or pooling in streams (6.2.3) is provided, because mining-specific imagery of these features was not found. This section also considers the spatial and temporal components related to each feature. In addition, this report presents information from mining subsidence experts, who provided site-specific examples and background information about surface features related to mining subsidence.

6.1 Subsidence Features Related to Room and Pillar Mining

This section describes common surface features that occur as a result of subsidence related to room and pillar mining. These surface features may develop suddenly, without warning, often long after mining operations have ceased. Section 6.1 highlights how depth of cover is directly related to the type of surface features that occur as a result of room and pillar mining-related subsidence and addresses the causes and mechanics of how these features form.

6.1.1 Sinkholes

Sinkholes are the most common form of subsidence in room and pillar mining (Figure 9; Whittaker and Reddish, 1989). Sinkholes are observed at the surface as either conical depressions or as a hole with vertical or overhanging sides (Whittaker and Reddish, 1989) and are typically on the order of a few feet to tens of feet in both diameter and depth (Gray et al., 1977). Sinkholes form as a result of progressive collapse of roof strata that propagates to the surface in the form of a column or cone, also known as a collapse chimney (Figure 10; Whittaker and Reddish, 1989). In order for a collapse chimney to reach the surface, the depth of overburden must be (a) sufficiently shallow or (b) caved material must be allowed to flow into the mine (Whittaker and Reddish, 1989). A sinkhole may not propagate to the surface if the upward migration of the collapse chimney is halted by competent strata or if the natural bulking of the caved material prevents further failure of strata (Gray and Bruhn, 1984). Sinkholes often form at three-way and (more commonly) four-way intersections of mined out areas in room and pillar mines (Gray and Bruhn, 1984). In the eastern United States, sinkholes typically do not appear when the depth of the overburden is greater than 100 feet (Gray and Bruhn, 1984).

Statistical analysis conducted by Gray et al. (1977) for 354 subsidence cases above the Pittsburgh coal seam indicated that most sinkholes formed where the depth of overburden was less than 50 feet (15 meters) thick. Their study also found that sinkholes were between 1.5 to 45 feet (0.5 to 14 meters) deep and 1.5 to 45 feet (0.5 to 14 meters) in diameter. The authors also concluded that over half of the subsidence events occurred over 50 years after mining had occurred.

In sloping terrain, sinkholes are often located close to the outcrop of coal seams (Whittaker and Reddish, 1989; Figure 11). Pillar collapse near coal outcrops is not very common because overburden depths are typically shallow (Whittaker and Reddish, 1989). The surface expression for sinkholes in sloping terrain is that of a conical depression, similar to the surface expression of sinkholes flat-lying terrain (Whittaker and Reddish, 1989).

6.1.2 Subsidence Troughs

Subsidence troughs can form in room and pillar mining as a result of pillars either collapsing or punching into the floor of the mine (Figure 12; Gray and Bruhn, 1984). Subsidence troughs may form concurrent with mining or long after a mine has been abandoned, due to coal pillars being weakened by spalling and weathering (Gray and Bruhn, 1984). Diameters of subsidence troughs typically measure about 1.5 to 2.5 times the overburden thickness, ranging from a few tens of feet wide to hundreds of feet in diameter (Gray and Bruhn, 1984). Gray et al. (1977) created a summation of subsidence experiences for mining above the Pittsburgh seam. They find that most subsidence troughs occurred where the depth of overburden was more than 50 feet thick. It is important to note the subsidence troughs differ from subsidence basins (discussed in section 6.2.1) in that subsidence troughs are nearly always elliptical in shape.

6.1.3 Portal Collapse

Mine portals serve as entry points to mines, and in the case of old abandoned mines, these features may collapse. When portals collapse, subsidence at the surface may result in depressions and/or small zones of convergent topography (Figure 13). Mine portals are readily observed from LiDAR as u-shaped notches that cut into sloping terrain (Figure 14). The size of mining portals is dependent on the scale of the mine operation. Thus, portals are sized appropriately for the necessary equipment and personnel entering the mine. Mine portals can sometimes be detected by piles of waste rock (slag heaps) extending into valleys or onto hillslopes. Mining portals also serve as indicators for possible subsidence-related features nearby.

6.2 Subsidence Features Related to Complete Extraction Mining

The following features occur as a result of either longwall mining or pillar retreat mining. Because these methods of mining result in complete removal of coal at depth, they are referred to as complete extraction mining. Some features in this section may also occur as a result of room and pillar mining-related subsidence (e.g., (6.2.2) landslides and rockfall or (6.2.3) pooling and dewatering of streams). However, only examples for the following features in this section were found in literature pertaining to complete extraction mining methods.

6.2.1 Subsidence Basins

Subsidence basins form as a result of vertical movements associated with complete extraction mining. The surface expression of a subsidence basin in flat terrain is a large, depressed (subsided) area (Figure 15). The dimensions of a given subsidence basin are dependent upon the area of coal removed or the number of pillars that have been removed. For longwall mines that are mined in parallel succession, a wave-like subsidence profile may develop within subsidence basins as a result of the pillars left between adjacent panels (Peng, 2006; Jeran and Adamek, 1988). For longwall mining, subsidence basins form nearly contemporaneous with mining. For example, surface subsidence has been observed to be about 90% complete when the mining face is 0.75H to 1.0H past a given monitoring point at the surface, where H is the depth of the extracted material below the surface (Gray and Bruhn, 1984). Residual movements related to total extraction are typically complete within two years after mining (Gray and Bruhn, 1984). In the case of room and pillar mining, loss of pillar support may occur suddenly or over a long period of time.

6.2.2 Heave Features

Heave features may occur as a result of horizontal movements at the base of valleys near or above areas of complete extraction mining (Figure 16; Kay et al., 2006). The horizontal movements result in compressive stress at valley lows, which can cause heaving in the up direction at the ground surface (Figure 16; Kay et al., 2006). Valley closures, where the valley sides move toward the center of the valley, and subsequent bulging/heaving in valley bottoms have been observed to occur naturally (Patton and Hendren, 1972). However, this phenomenon is generally understood to be accelerated by mining (Kay et al. 2006). A site-specific example of stream heave in an unnamed tributary of Wheeling Creek in northern West Virginia is provided in Figure 17. The heave feature at the unnamed tributary of Wheeling Creek was consistent with recent longwall mining operations, and based on site investigations, was determined to be a subsidence feature (Ball, 2013).

6.2.3 Landslides and Rock Fall

Landslides may occur as a result of underground mining when changes are made to the angle of the slope (e.g., steepening) or to the hydrologic regime. Subsidence is known to result in extensive tensile forces on the upslope side of mined out areas as well as steepening of hillslopes (Whittaker and Reddish, 1989). Tensile strain can result in increased infiltration to the subsurface (Whittaker and Reddish, 1989) and subsequent fracturing of strata can change the flow path of groundwater (Peng, 2006). Either of these changes to the hydrologic regime may cause a decrease in slope stability as a result of increased pore pressures within the subsurface material. Whittaker and Reddish (1989) point out that when mining in areas of sloping terrain, special consideration should be given to the stability of hillslopes.

Rockfall has been observed to occur coincident with longwall mining in Australia. Findings from Kay et al. (2006) at the Tower Colliery in Australia are summarized as follows: an increase in the amount of cliff instabilities was observed above longwall panels following coal extraction. No rockfalls were reported beyond the edges of longwall panels and only a few instabilities have been reported when longwall mining occurred at depths greater than about 1300 feet (400 m).

6.2.4 Pooling and Dewatering of Streams

Pooling in streams can occur from changes in stream gradients as a result of longwall mining-related subsidence. When longwall mining occurs beneath stream channels, topographic highs may form as a result of differential settlement over the chain pillars that remain between longwall panels (email communication August 2013 Steve Kite, professor of geomorphology at West Virginia Univ.). The size of pools that develop in stream channels as a result of differential settlement is related to the amount of water available and the geometry of the stream channel. A common remedial technique to restore stream gradient and pre-longwall mining flow conditions is to mine out the coal pillars beneath the stream (known as “cutting the gates”) (email communication August 2013, Steve Kite WVU). When coal pillars beneath pooled areas of streams are removed, the topographic highs responsible for the ponding are lowered and streamflow may be restored.

Dewatering of streams may occur as a result of bedrock becoming fractured in streambeds after longwall mining (Figure 18; Kay et al., 2006 and Holla and Barclay, 2000). When bedrock streams are fractured, surface flow may be diverted into discontinuities and flow into the subsurface, later reemerging down gradient (Kay et al., 2006). Leakage may also occur in fractured rockbars (bedrock bars that serve as natural dams), where water pooled behind the rockbar is able to flow out (Kay et al., 2006).

6.3 Features Coincident with Both Room and Pillar and Complete Extraction Mining

The following features occur as a result of either room and pillar mining or complete extraction mining. In some cases, for example in southern West Virginia, mining of multiple coal seams above one another is conducted using both room and pillar mining and longwall mining methods. In these circumstances it may be difficult to identify which method of mining is responsible for a particular feature.

6.3.1 Cracks/Fissures

When longwall mining and/or room and pillar mining results in subsidence at the surface, cracks/fissures can develop as a result of tensile strain. The size of these features is variable, ranging from sub millimeter discontinuities to fissures that are on the order of tens of feet wide, by several tens of feet deep and hundreds of feet long (Figure 19 and Figure 20; Ingram, 1989). Typically, cracks/fissures occur along the edges of subsidence basins, where tensile strains are the greatest (Peng, 2006). Overburden lithology, strain history, depth of mining, dimensions of coal removed, and time can all influence the manner in which cracks form. In the case of room and pillar mining tension cracks may develop along the edges of subsidence troughs and sinkholes as a result of differential horizontal movements.

6.3.2 Linear Sinks

Linear sinks (depressions) are commonly observed in-line with cracks/fissures in LiDAR-derived DEMs in southern West Virginia (Figure 21). Nick Schaer, a geologist with the WVDEP specializing in mining-related subsidence, first called attention to these features. The sinks are often in-line with the location of large cracks/fissures and appear as circular depression, measuring from a few feet to tens of feet in diameter from LiDAR. Typically, sinks have similar diameters as the width of the crack/fissure that they are in line with (Figure 21), thus, it is inferred that the sinks represent a continuation of these features. It is likely that the sinks are the result of soil and weathered bedrock that is failing into voids within the subsurface created by the cracks/fissures. However, because these features have only been observed from LiDAR, field characterization is needed to better understand how linear sinks manifest at the surface. These features are important to note because fractures may not always reach the surface, however linear sinks may still develop.

6.4 Other Features and Considerations with Underground Mine Subsidence

Hummocky/uneven terrain may develop within subsidence basins as a result of compressive or tensile strains associated with underground subsidence. Compressive forces in the center of subsidence basins may result in heaving, whereas the sides of subsidence toughs may exhibit graben structures due to tensile forces. Hummocky/uneven terrain may also develop in areas of room and pillar mining. One characteristic example of hummocky/uneven terrain is in Sheridan Wyoming, where an abundance of sinkholes have developed as a result of shallow workings from room and pillar mining (Figure 22). Norell (1970) observed that the presence of hummocky/uneven terrain resulting from mining-related subsidence may be used for orchards. Norell noted that orchards were ideal agricultural use of hummock/uneven terrain because the soil is well drained and unsuitable for conventional row crops due to difficulty in plowing the uneven ground. Thus, orchards may be a possible indicator of mining-related subsidence and should be kept in mind when reviewing Google Earth and aerial imagery.

Faults near and above areas of underground mines may be reactivated as a result of subsidence (Dunrud, 1984). Faulting may give rise to irregular mining subsidence patterns, with the potential for surface steps (scarps) to develop (King, Whittaker, and Shadbolt, 1974). Scarps with surface displacements as much as 14 inches (35 centimeters) for a linear length of about 490 feet (150 meters) have been observed as a result of fault-controlled subsidence in Salina, Utah (Dunrud, 1984). Normal faults are the most likely type of fault to move under the effects of subsidence (Whittaker and Reddish, 1989). Normal faults are more likely to move as a result of underground mining subsidence because, being tensional features, friction plays a lesser role than other types of faults (Whittaker and Reddish, 1989). In contrast, the compressional stresses in reverse faults decreases in the sensitivity to subsidence related reactivation (Whittaker and Reddish, 1989).

How water may impact the amount of subsidence observed at the surface is summarized by Dunrud (1984): In areas of Europe and the United States where there is abundant groundwater and surface water present, subsidence has been observed to be greater than 89% of the total extraction thickness at depth. In contrast, for areas of the United States where mines are dry, the maximum subsidence observed at the surface is only 50% to 70% of the extracted thickness.

When mining-related subsidence occurs, groundwater flow may be affected (Peng, 2006). For example, loss of water in aquifers has been observed in West Virginia coincident with longwall mining, with many instances of dewatering of domestic wells occurring along ridgetops (personal communication, Steve Ball, November, 2013). If groundwater is able to daylight in areas of hillslopes that were previously relatively dry, slope stability issues may arise. Also, loss in water quality may result if the groundwater flow path is changed and water is able to intercept contaminants.

7 Summary

Subsidence related to underground coal mining can present serious problems to new and/or existing infrastructure, utilities, and facilities. Heavy equipment driving over the ground surface during construction processes may punch into voids created by sinkholes or cracks, resulting in injury to persons and property. Abandoned underground mines also may be full of water, and if punctured, can flood nearby areas. Furthermore, the integrity of rigid structures such as buildings, dams and bridges may be compromised if mining subsidence results in differential movement at the ground surface. Because of the hazards associated with underground coal mines, it is important to know the location of mines near existing or proposed buildings and/or infrastructure. By investigating surface features related to underground coal mining subsidence these hazards can be better understood, and if necessary, either mitigated or avoided altogether.

When conducting geologic hazard assessments, several remote investigation methods can be used to observe surface features related to underground mining subsidence. LiDAR-derived DEMs are generally the most useful method available for identifying these features because the bare earth surface can be viewed. However, due to limitations in the availability of LiDAR data, other methods often need to be considered when investigating surface features related to underground coal mining subsidence, such as Google Earth and aerial imagery. Mine maps, when available, can be viewed in tandem with these datasets, potentially improving the confidence of any possible mining subsidence-related features observed remotely.

In complete extraction mining, movements at the surface can develop subsidence basins. Horizontal and vertical movements, tilt, and curvature are the fundamental parameters involved with the development of subsidence basins. These parameters are important to consider with regard to damage of surface structures. For example, surface structures located in areas with the large differential movements and/or high curvatures will be the most likely areas to be damaged.

Underground mine subsidence-related movement within the overburden is directly related to how features manifest at the surface. Observations indicate that overburden movements related to longwall mining result in four zones of movement within the stratigraphic column, including: (1) the caving zone, (2) the fractured zone, (3) the continuous deformation zone, and (4) the soil zone (Peng, 2006). While movements within all of these zones are responsible for causing subsidence at the surface, it is the movement within the continuous deformation zone and the soil zone that relate the most to the type of features observed at the surface.

Based on mining technique, many different types of features can occur at the surface. For example, in room and pillar mining, sinkholes commonly develop, whereas sinkholes are not known to occur as a result of longwall mining. Similarly, heave features have not been reported (to the knowledge of the author) coincident with room and pillar mining. The depth and type of mining, geologic conditions, hydrologic conditions, and time are all factors that may influence the type of features that manifest at the surface. This guide provides investigators a basic understanding about the size, character and conditions regarding various surface features that occur as a result of underground mining subsidence.

8 Limitations

It is possible that other subsidence-related geomorphic features exist that are not described in this paper. This paper sought to conduct a literature review of known subsidence features, while also corroborating with local experts. However, due to limitations on time, this paper is not an exhaustive examination.

This study is limited on available financial resources. For example money was not available to purchase literature pertaining to the subject of underground mining related subsidence. Thus, this study is based on literature available through the University of Washington and free within the public domain.

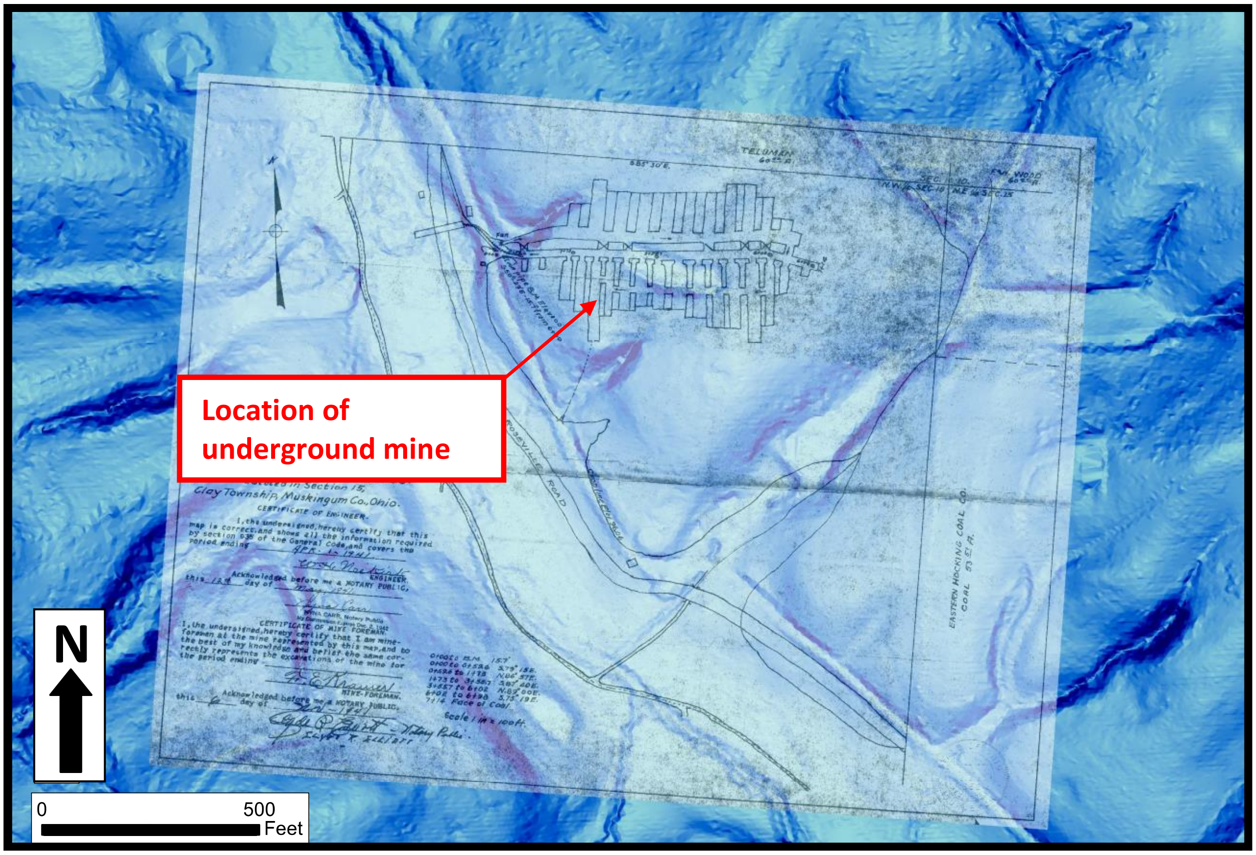

Figure 1. Image of LiDAR-derived DEM classified to show varying degrees of slope (steeper slopes are darker blue). A geospatially referenced map of an abandoned room and pillar mine is overlain on the LiDAR imagery. Note, the georeferenced mine map does not match up perfectly with the LiDAR image, this may be a result of changes to the land surface since the map was drawn in 1941, and/or the map was drawn incorrectly. Historic imagery may assist in aligning the image. Ponded water is present at the location of the mine, possibly indicating mining-related subsidence has taken place. However, further investigations are required to determine the origin of the ponded water. LiDAR downloaded from Ohio Geographically Referenced Information Program; mine map courtesy of Ohio Department of Natural Resources.

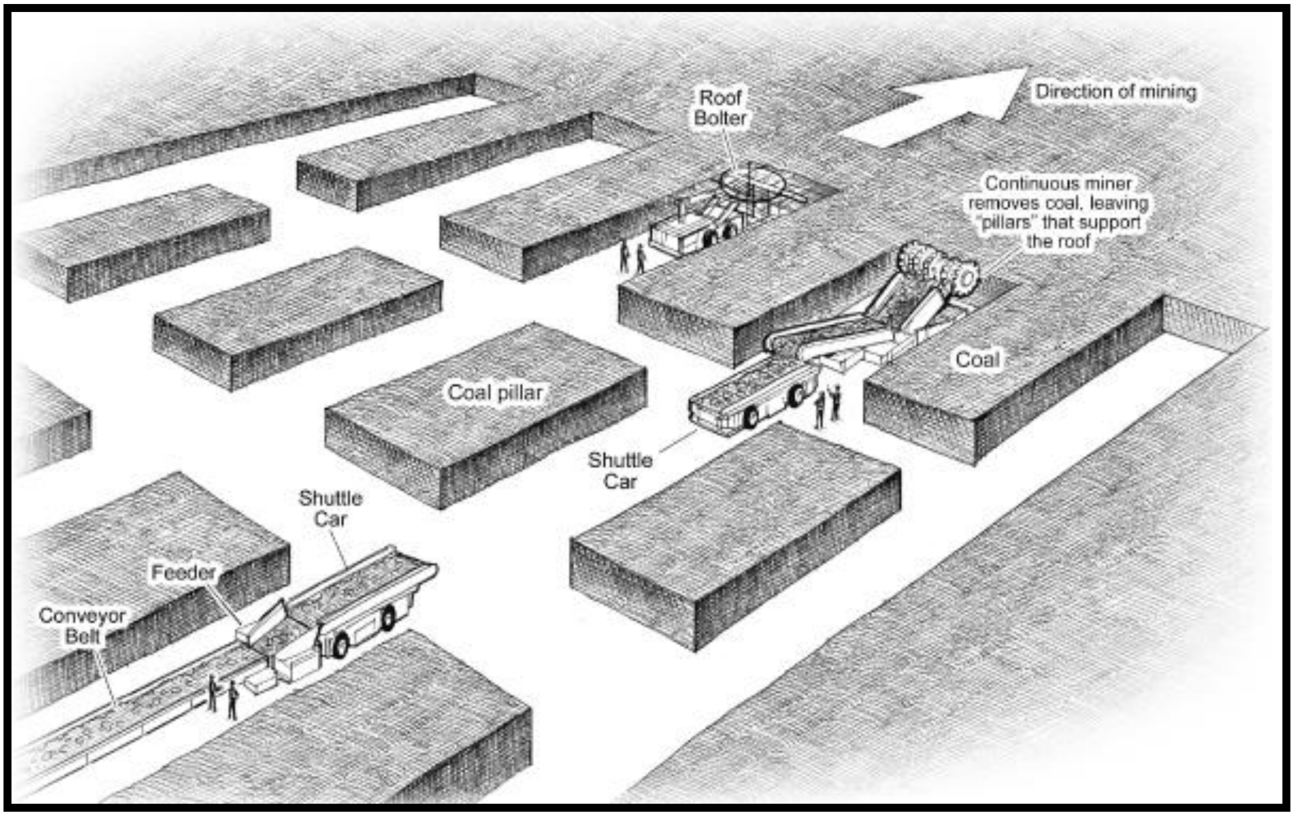

Figure 2. Diagram of modern room and pillar mining. The "rooms" in room and pillar mining refers to the extracted areas between the coal pillars. Reproduced from Arch Coal, Inc. (2009)**.**

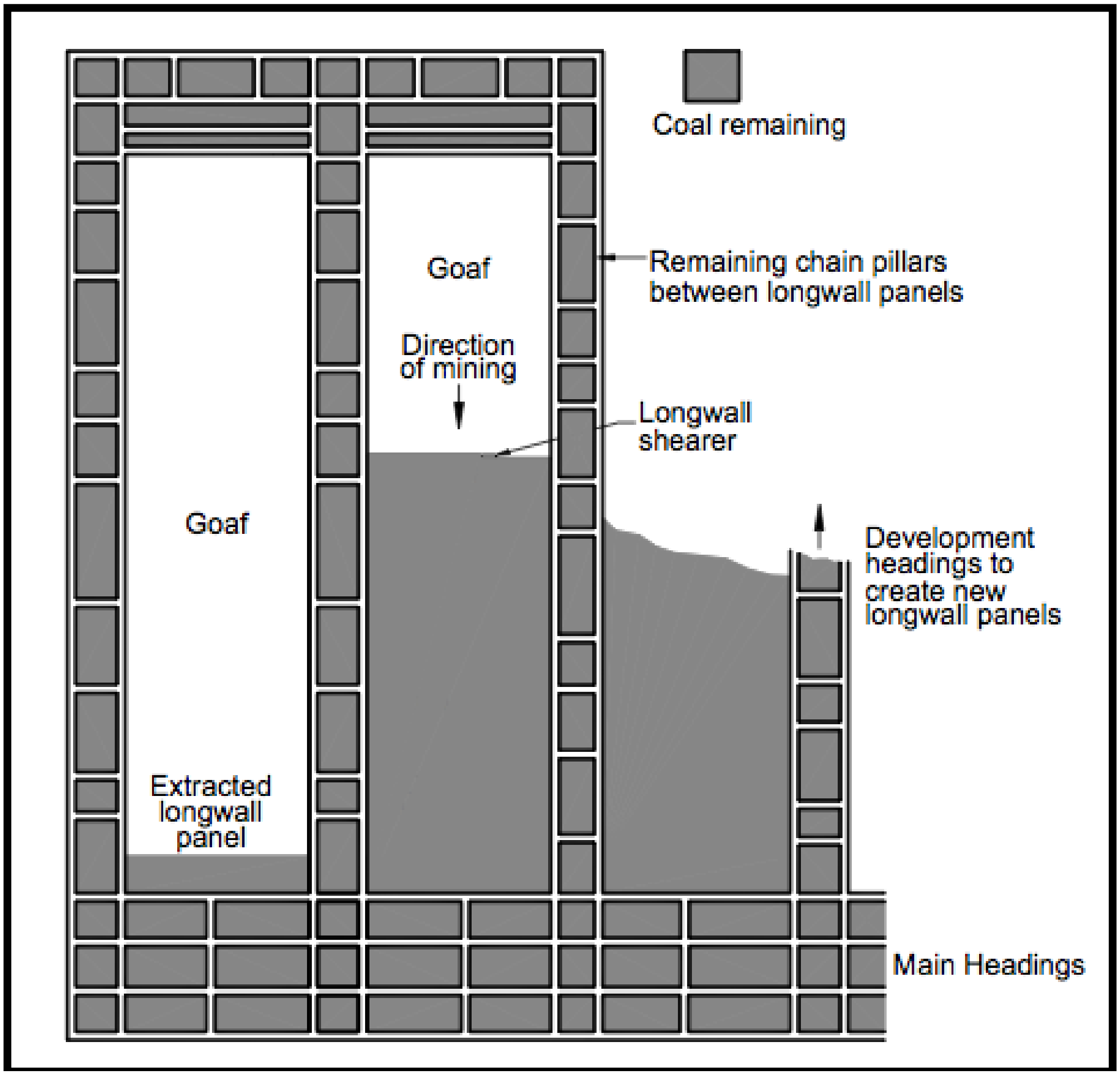

Figure 3. Plan view of a typical longwall mine. Longwall panels are often mined in succession, separated by chain pillars. The white areas indicate regions where coal has been extracted and the gray represents unmined portions (i.e., the pillars and longwall panels to be mined). Reproduced from Mine Subsidence Engineering Consultants (2007).

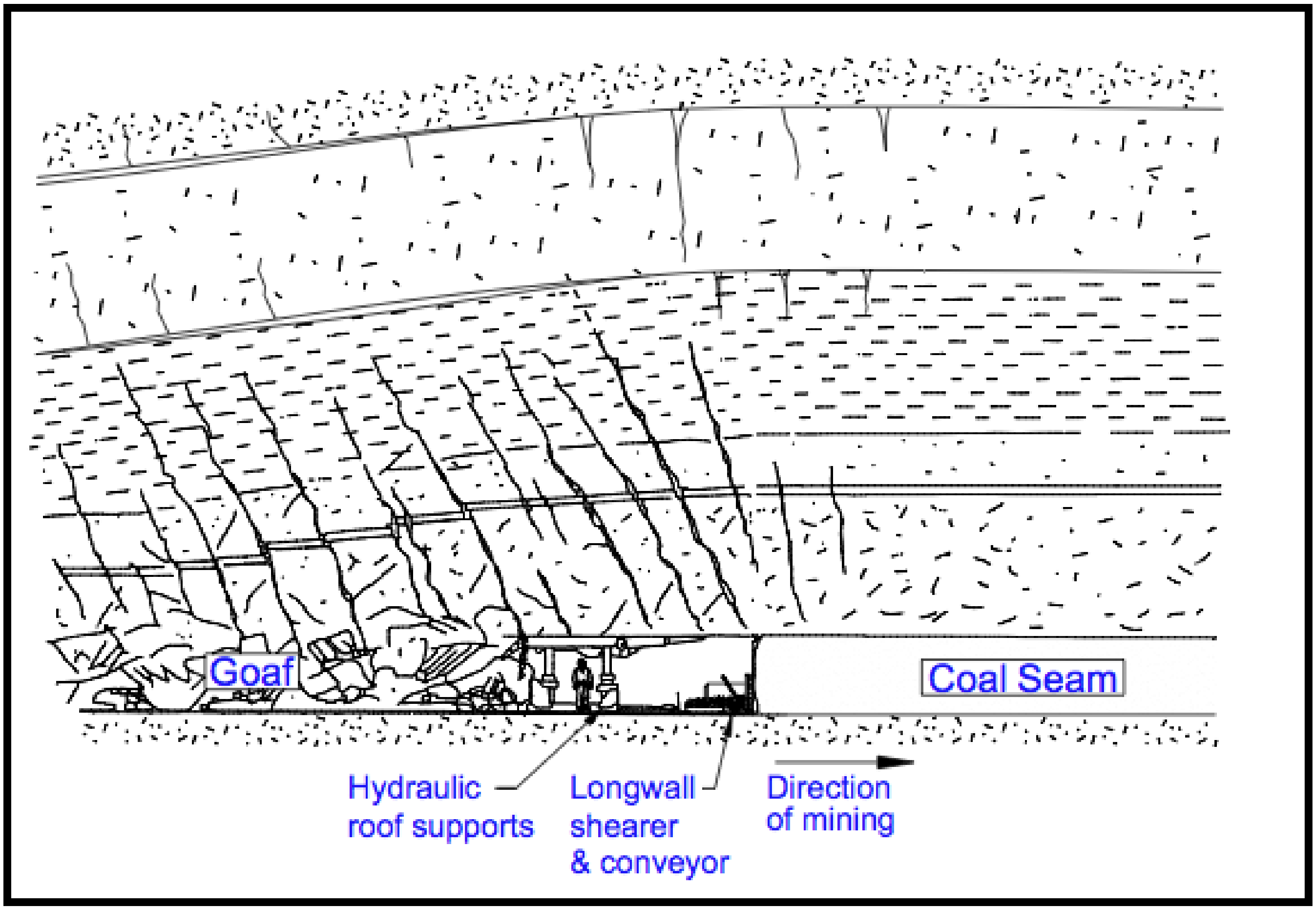

Figure 4. Side view of longwall mining illustrating the location of the goaf area where roof material has collapsed into the mine. This figure also indicates the positioning of equipment and personnel during longwall mining operations. Reproduced from Mine Subsidence Engineering Consultants (2007).

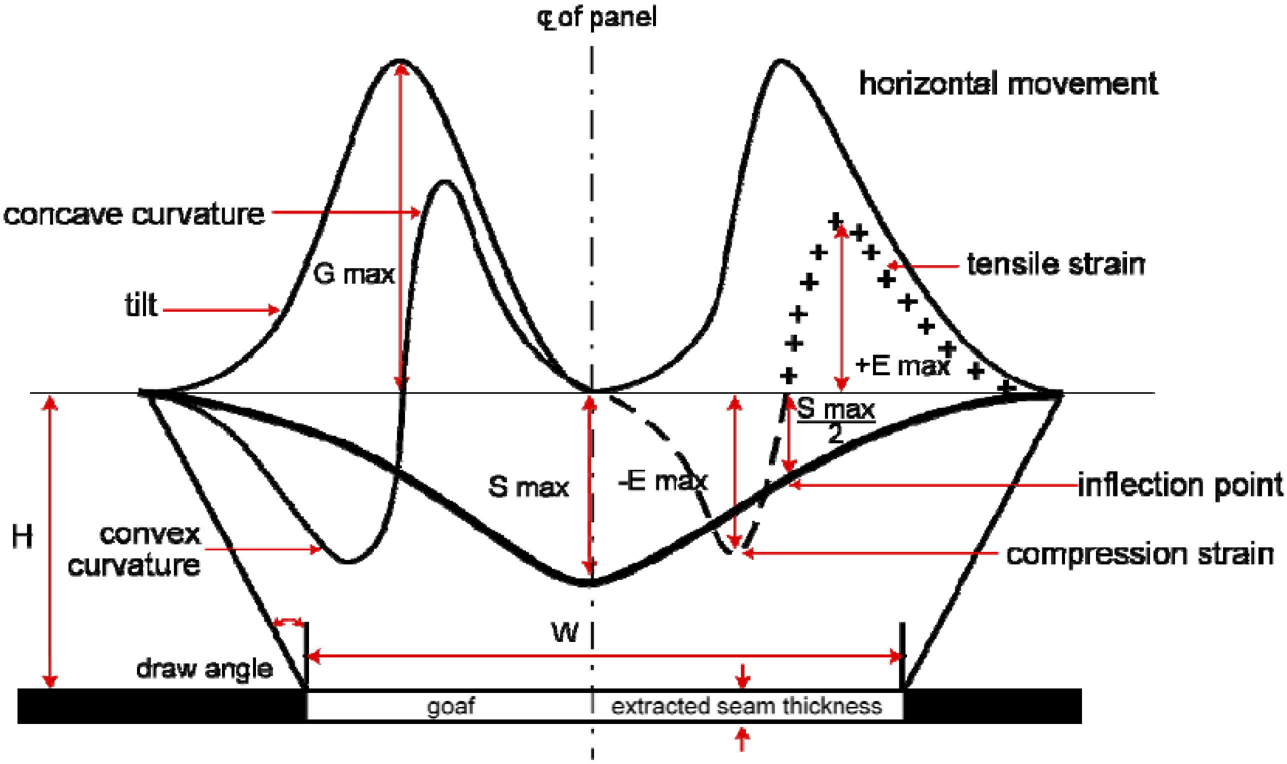

Figure 5. Subsidence parameters related to subsidence basins. The primary surface subsidence parameters include maximum subsidence (Smax), maximum ground tilt (Gmax), Maximum compressive (-Emax) and tensile (+Emax) ground strains, and minimum radius of ground curvature (Rmin). Extracted seam thickness (T), depth of cover (H), width of material removed (W), and the type of material in the goaf all determine the magnitude of subsidence. In Parsons and Brinckerhoff (2007) from Holla and Barclay (2000).

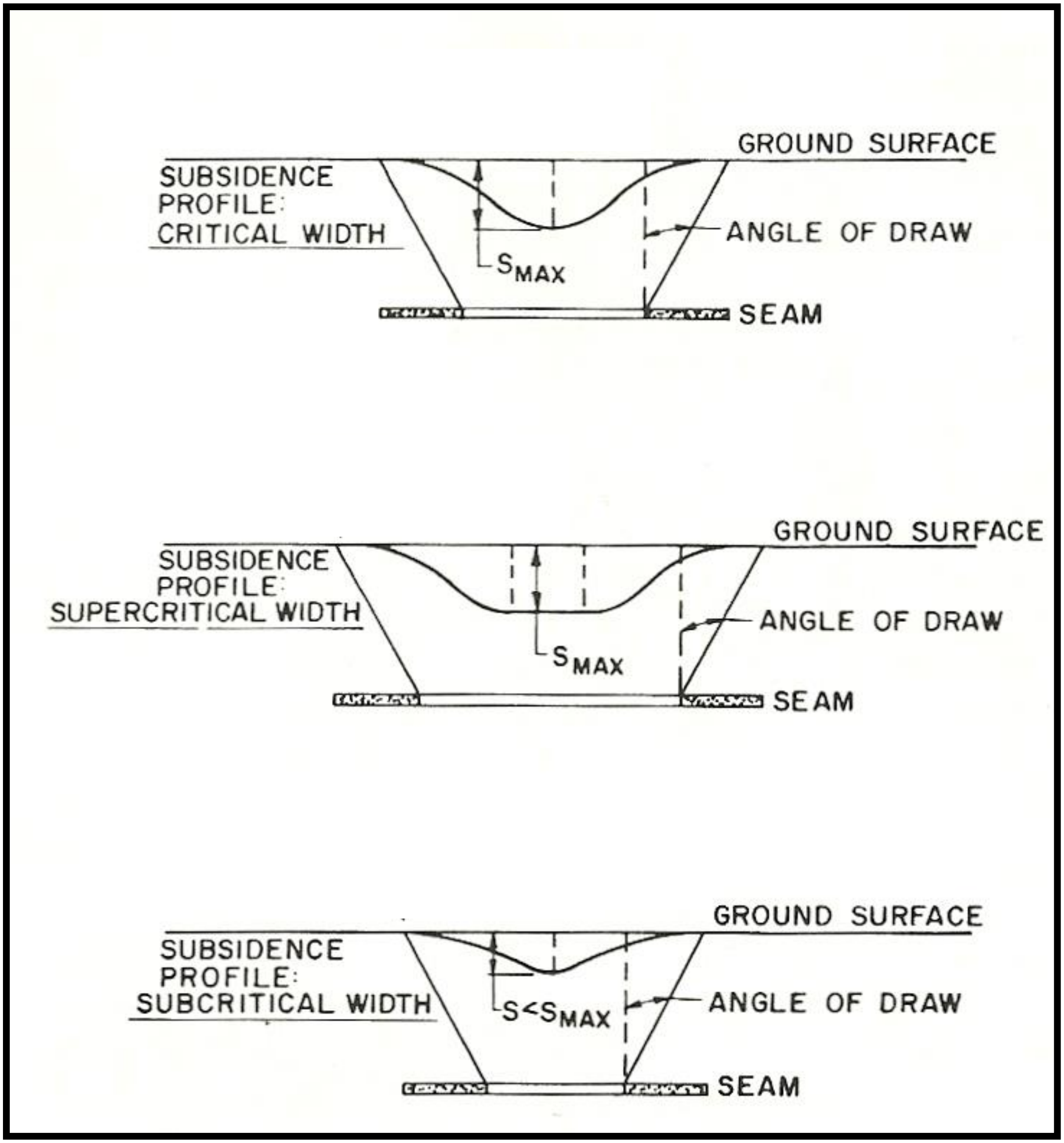

Figure 6. Critical, subcritical, and supercritical widths. Reproduced from Gray et al. (1974).

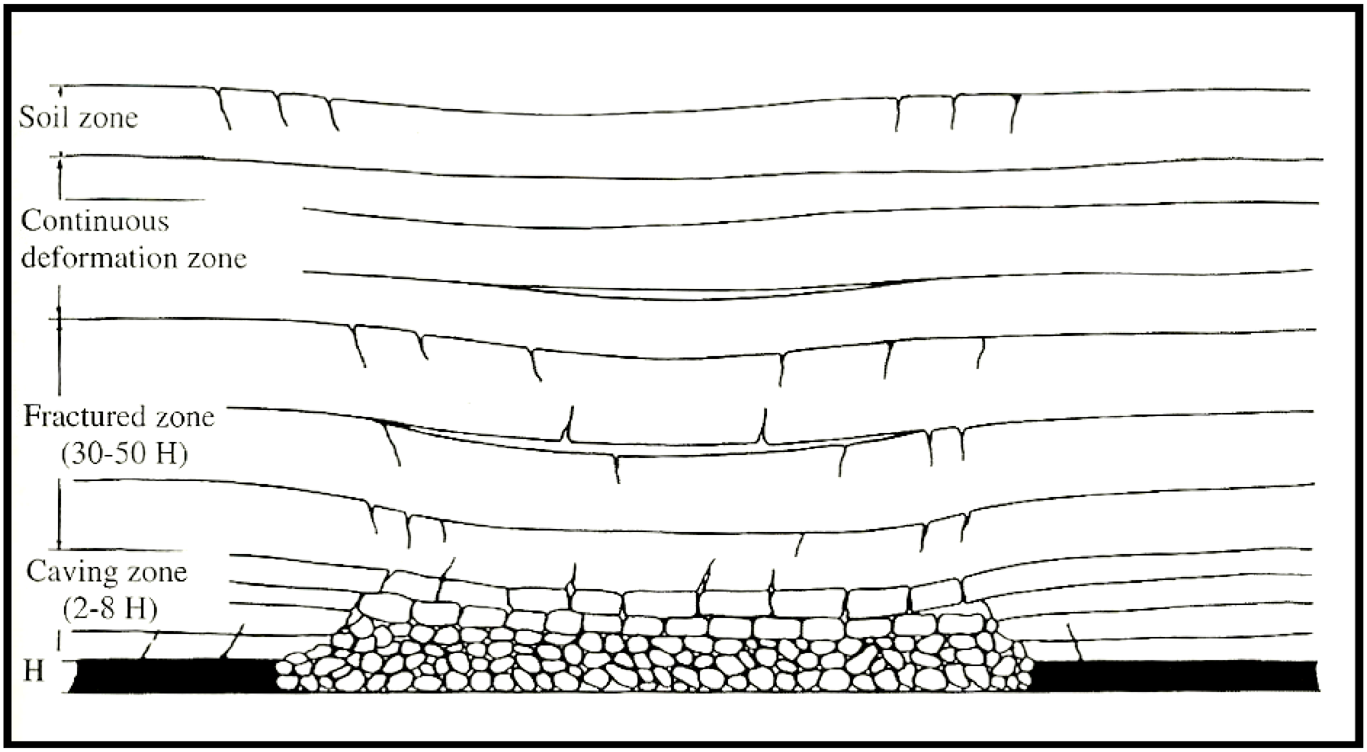

Figure 7. Overburden movement resulting from longwall mining. From Peng (2006).

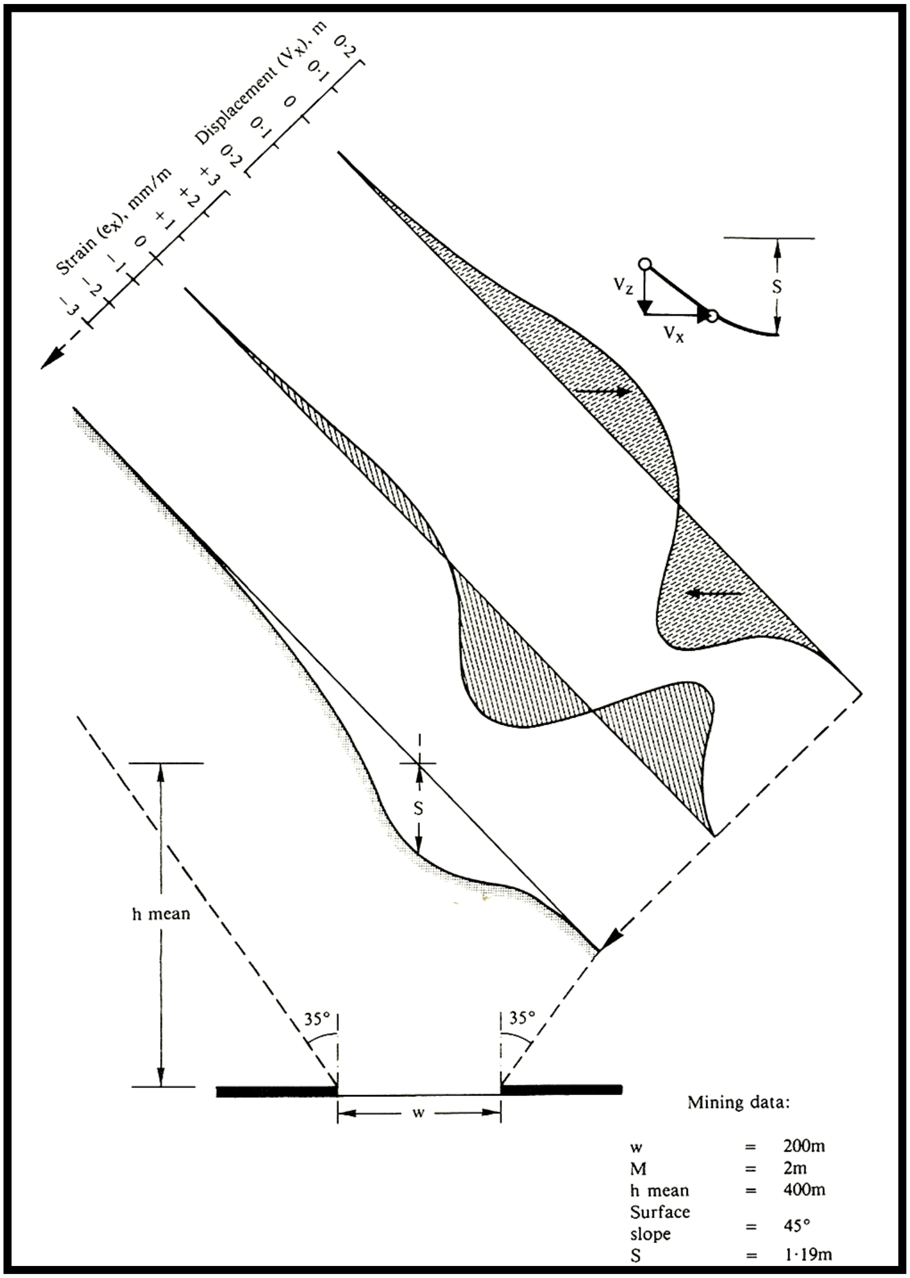

Figure 8. Subsidence profile calculated using the influence function method for a longwall panel extracted with a surface slope of 45 degrees. The influence function method considers how the influence of adjacent areas of extracted material at depth affects subsidence at the surface. Notice that the post subsidence profile results in steeping at the upslope side of the extracted area and a decrease in the slope angle on the downslope side. The symbols used in this figure represent the following: w = width of extracted area, M = height of extracted coal seam, h mean = average height of the surface above the extracted area, and S = maximum subsidence at the surface (Whittaker and Reddish, 1989).

Figure 9. Image of sinkhole resulting from underground coal mining in Ohio. Image from Norell (1970).

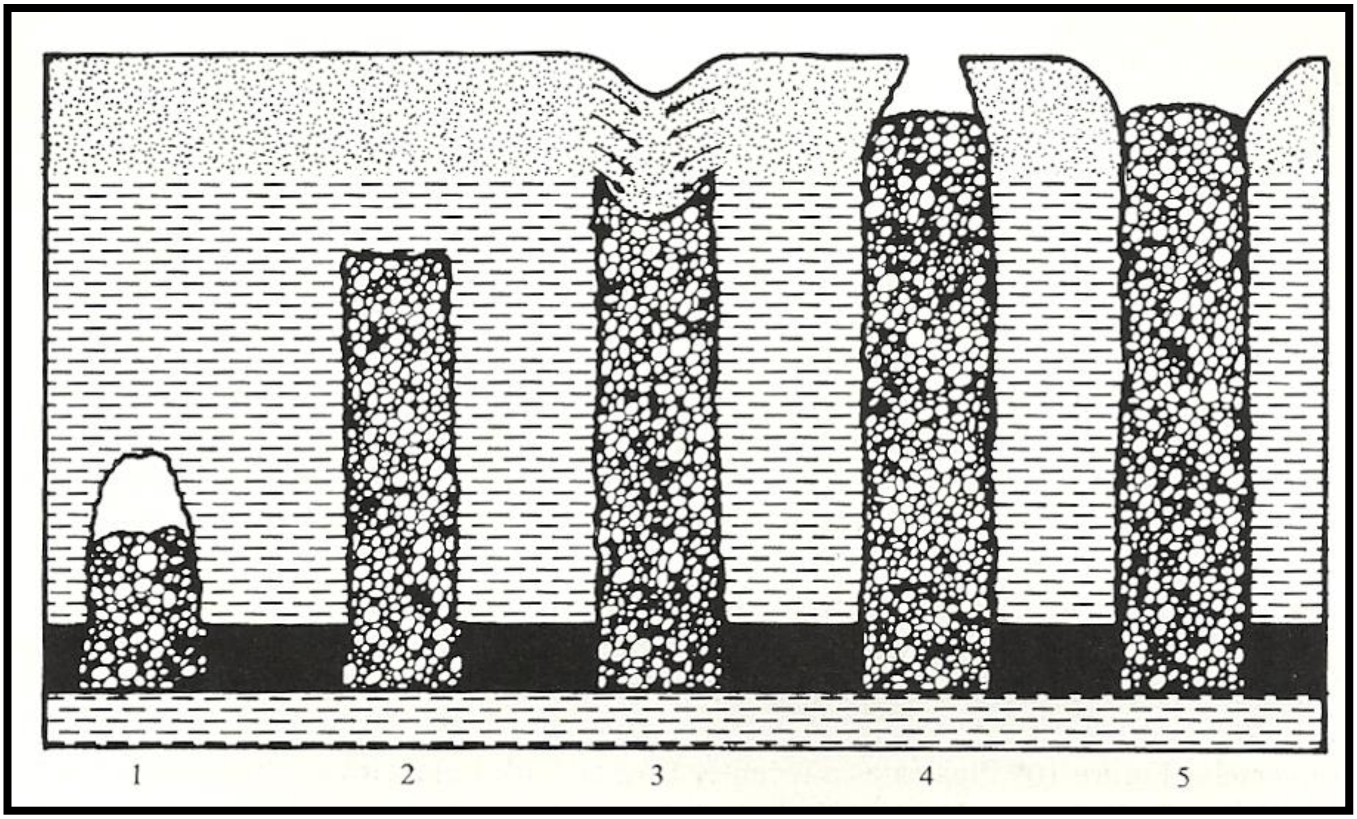

Figure 10. Collapse chimney and sinkhole development. (1) Shows a void above strata that has collapsed into a mine. If the natural bulking ability of the material is great enough, the collapse chimney may not reach the surface (2); (3) shows the condition of the collapse chimney reaching the surface, due to either (a) shallow depth of cover or (b) because material is able to flow into the mine. If further propagation of the collapse chimney is possible due to condition (a) or (b), then the collapse chimney can daylight at the surface in the form of a hole with overhanging sides (4); the result of surface material sloughing into the void created in (4) can result in a sinkhole profile similar to (5). Reproduced from Whittaker and Reddish (1989).

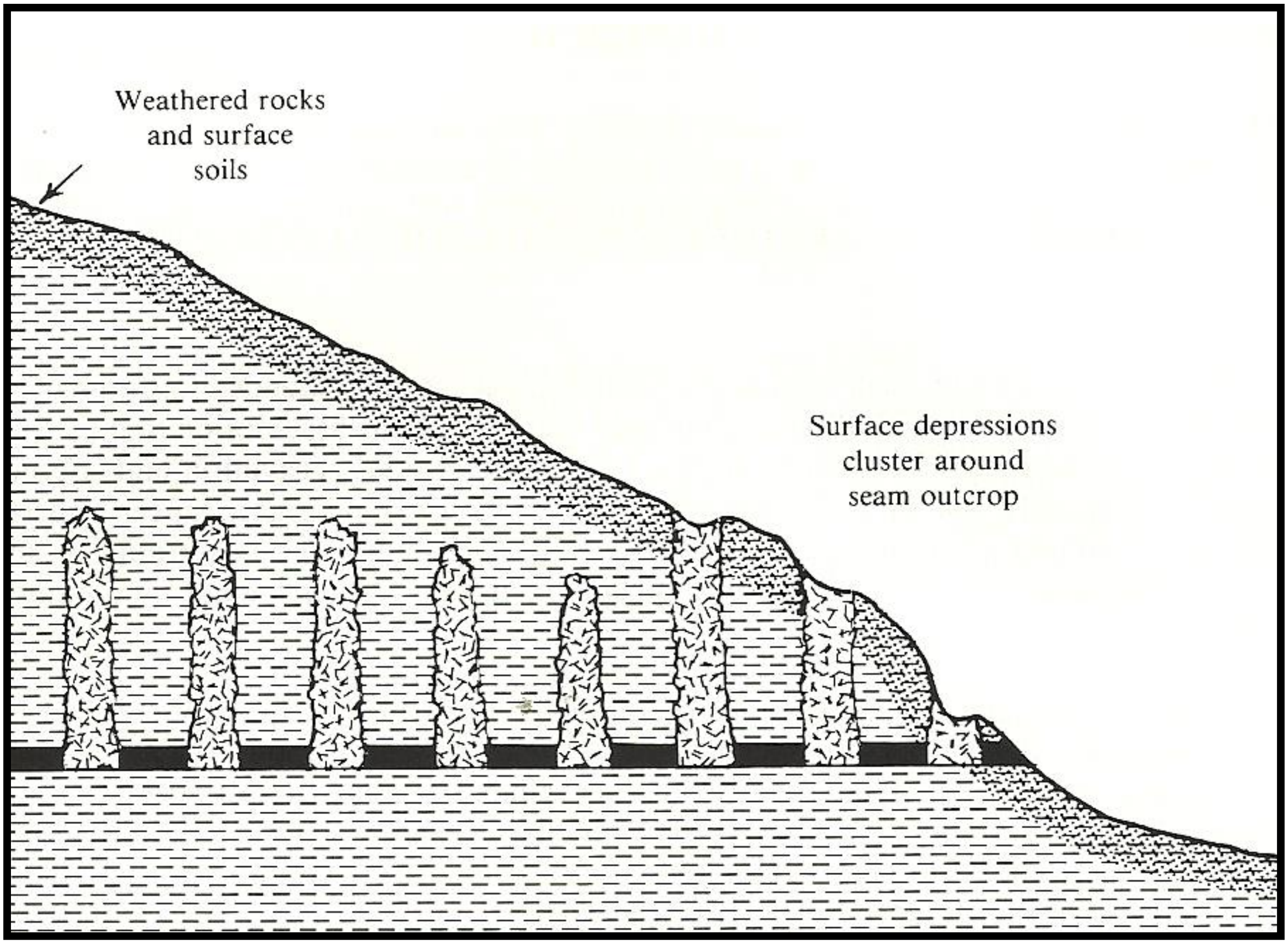

Figure 11. Subsidence in sloping terrain related to room and pillar mining. Note that sinkholes are mostly concentrated near the outcrop. Reproduced from Whittaker and Reddish (1989).

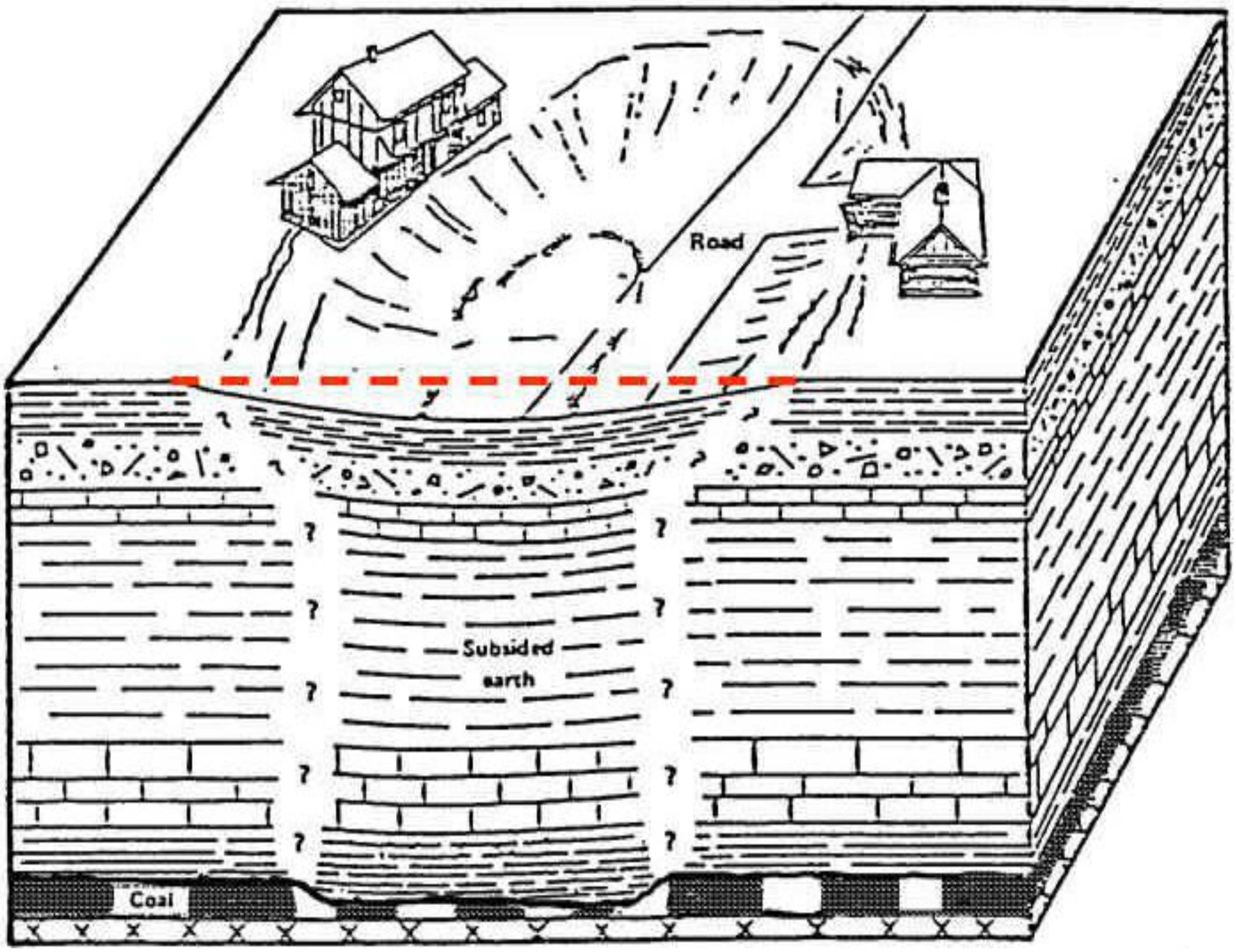

Figure 12. Diagram showing development of a subsidence trough. Note that the coal pillars in this example are crushed. Subsidence troughs may also develop as a result of pillars punching into the floor of the mine. Retrieved from: http://www.aegweb.org/images/students/minesubsidence.jpg?sfvrsn=0

Figure 13. Photograph of portal collapse (location A in Figure 11). Nick Schaer, WVDEP standing immediately downslope of a portal collapse. The portal collapse is indicated by the approximately 5-foot step and zone of convergent topography below it.

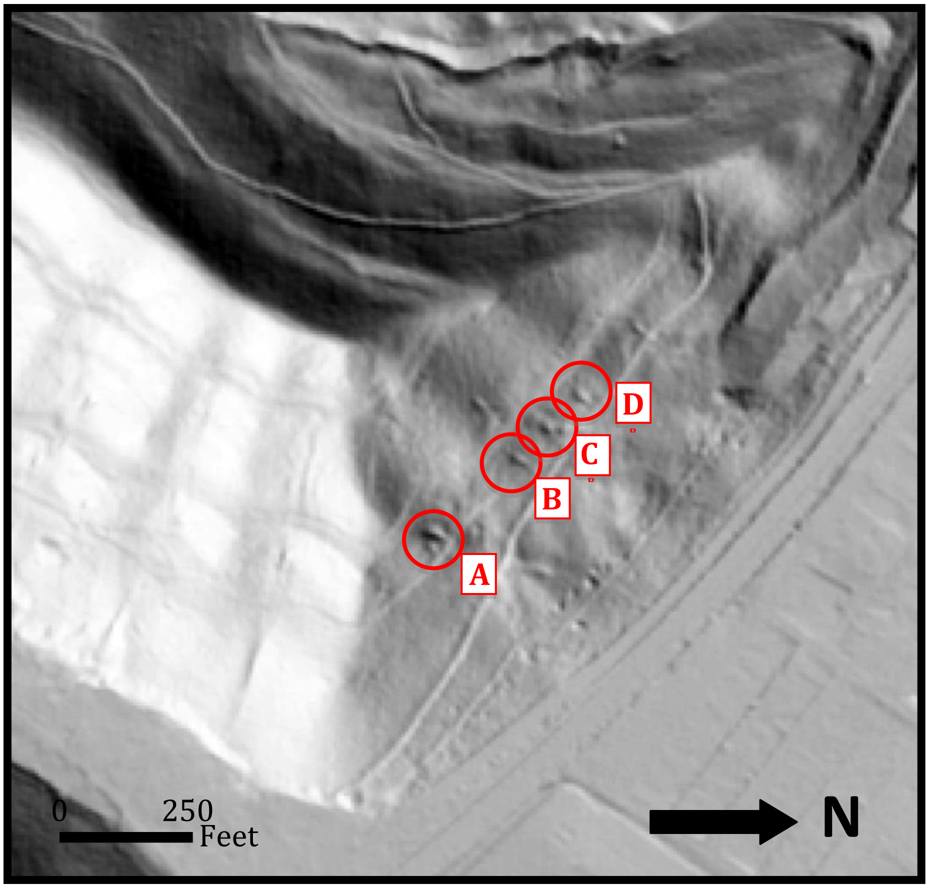

Figure 14. LiDAR-derived hillshade showing portal collapses (A-D). Also note the other mine entrances that appear as divots along the hillside. Image courtesy of Nick Schaer, WVDEP. Scale is approximate.

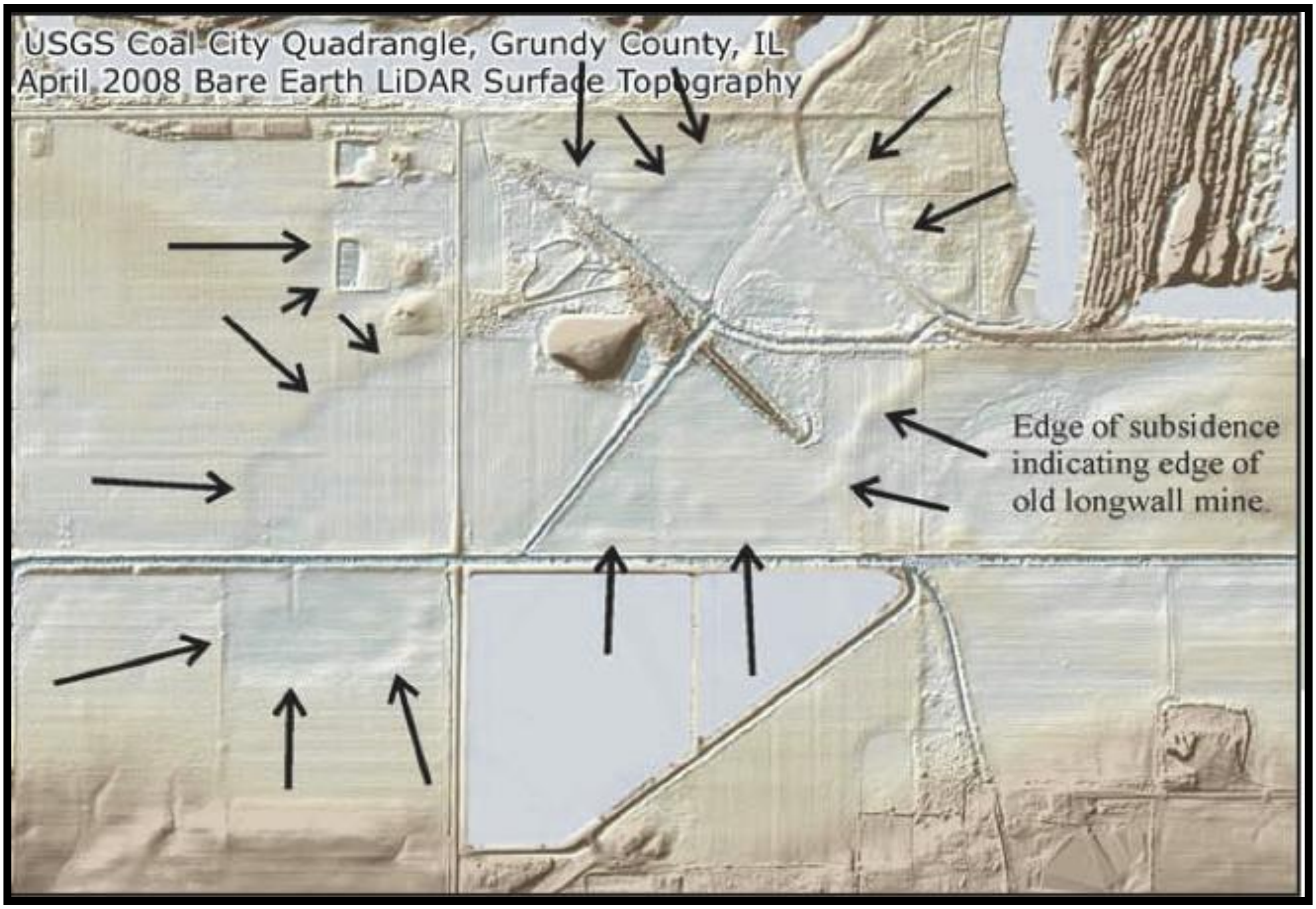

Figure 15. Bare earth LiDAR image showing a subsidence basin related to ground subsidence from old longwall mining in flat terrain. Roughly 2 feet of vertical ground subsidence is observed in this image nearly 100 years after mining had taken place. Image retrieved: www.crystal.isgs.uiuc.edu

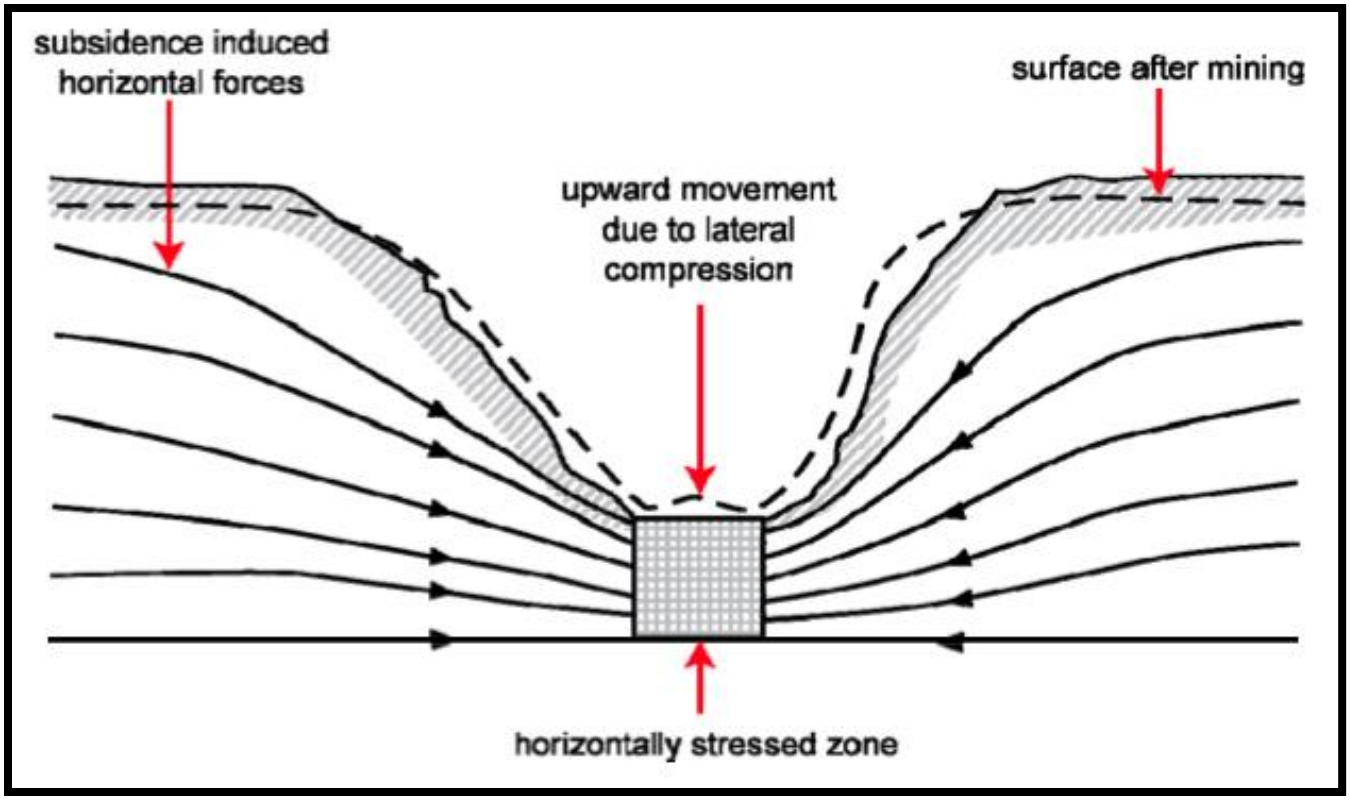

Figure 16. Conceptualized stress and surface movements related to longwall mining. This figure only shows the movements at the near surface as a result of mining subsidence at depth. The surface profile after mining results in closure of the valley sides and valley floor heaving/bulging in the horizontally stressed zone. Reproduced from Parsons and Brinckerhoff (2007), originally from Holla and Barclay (2000).

Figure 17. Heave feature, from mining subsidence, in bottom of unnamed tributary of Wheeling Creek located in northern study area. No scale is available for this image; however, the tree that has fallen over likely measures about 1-2 feet in diameter. Image courtesy of Steve Ball, WVDEP.

Figure 18. Image showing crack in dewatered streambed coincident with longwall mining. Image courtesy of Steve Ball (WVDEP).

Figure 19. Oblique aerial view of ground crack that measures about 300 feet (91 meters) long (above red line). Crack is located in the southern West Virginia. Coal mining surface operation can be seen in the background. The parallel/repeating sets of black lines in the image represent tree shadows. Image from Google Earth.

Figure 20. Oblique aerial image of a linear fissure in southern West Virginia. About 300 feet (91 meters) of the fissure is visible in this image. The fissure measures about 15 feet (4.5 meters) at its widest. Three underground coal mines are located beneath this fissure. Image from Pictometry.

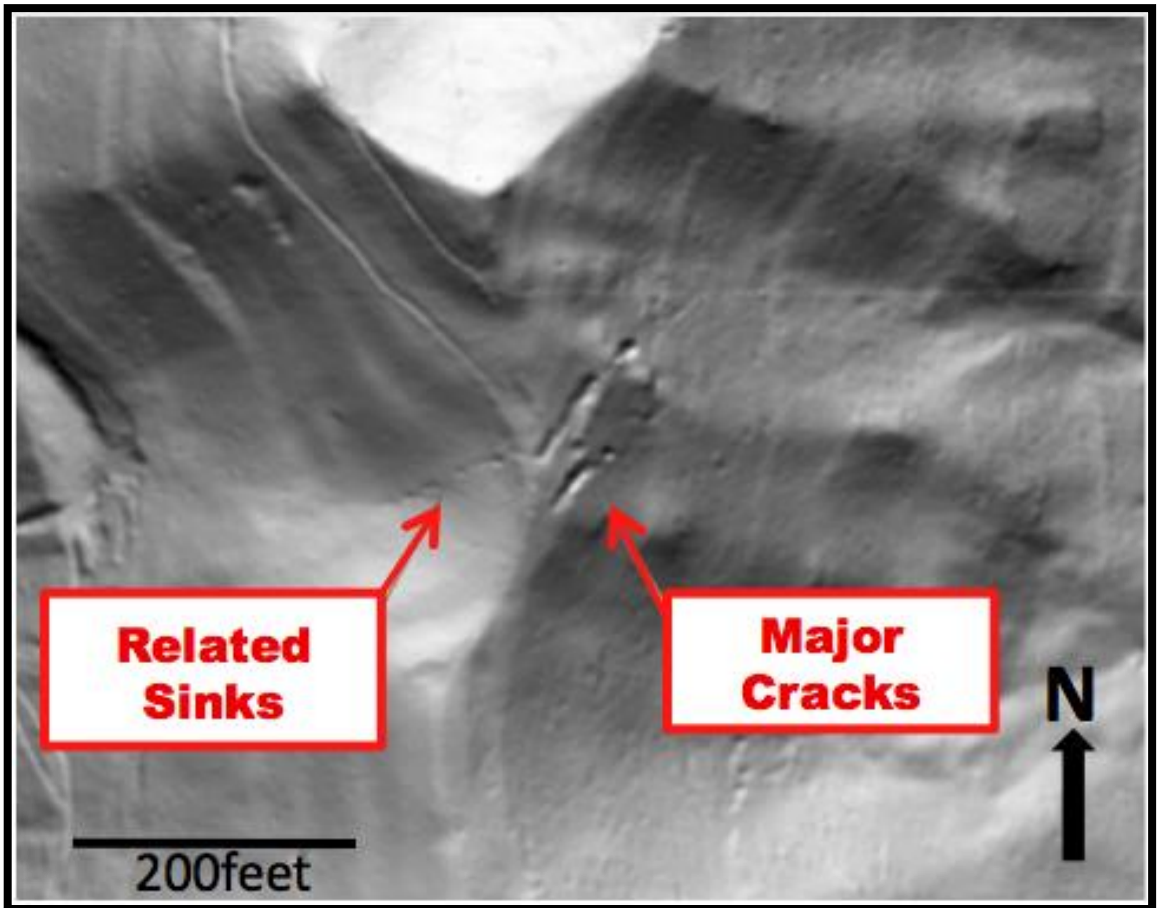

Figure 21. Cracks and related sinks in southern West Virginia, where multiple coal seams have been mined in stratigraphic succession. Image courtesy of Nick Schaer, Geologist, WVDEP. Scale is approximate.

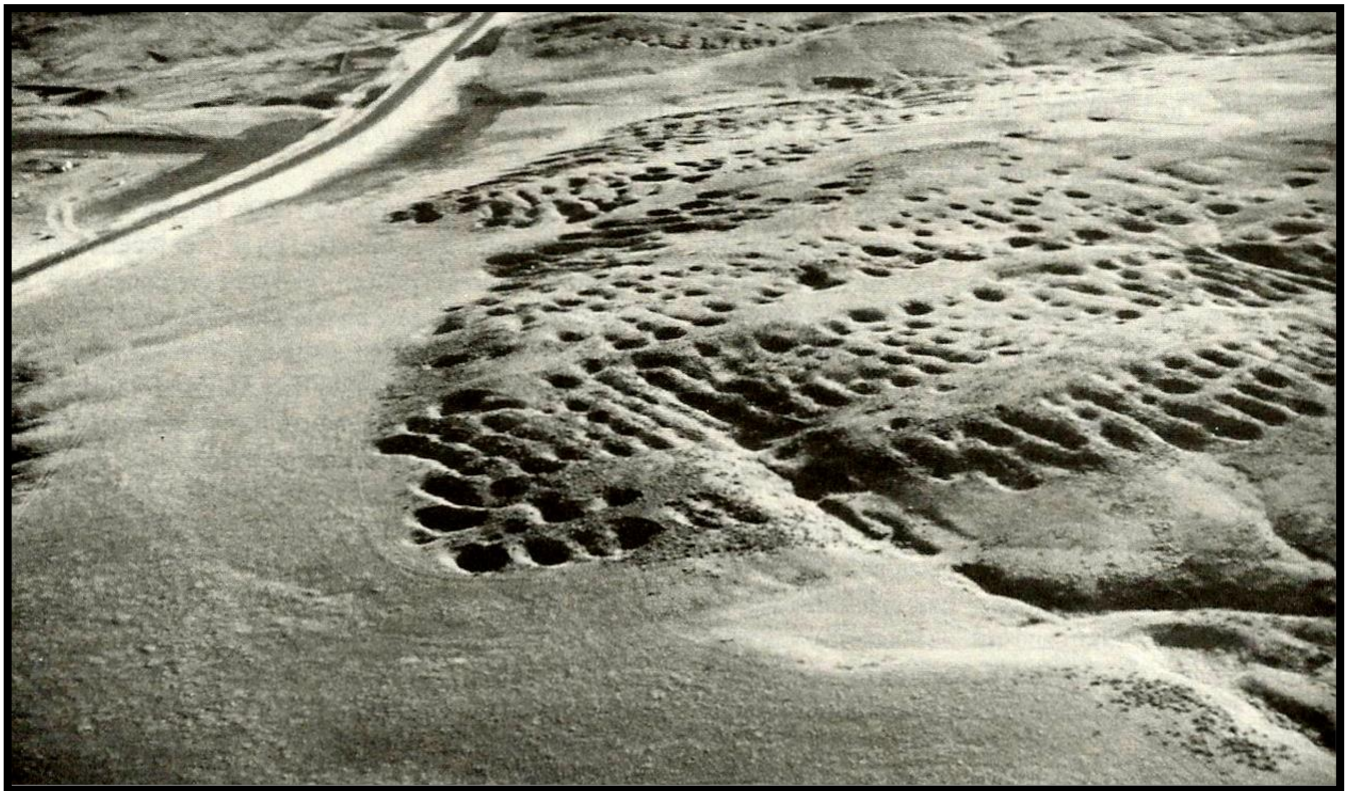

Figure 22. Sinkholes resulting in uneven/hummocky terrain. The sinkholes are related to bord and pillar, or post and stall mining methods. Bord and pillar, and post and stall mining are types of room and pillar mining methods that leave elongated pillars in place. The subsidence features in this image are located in the Sheridan, Wyoming area. The depth of cover above the mine in this image is about 5 to 45 m. The road located on the upper left of the image provides a relative scale. Image taken Nov. 1981. Reproduced from Dunrud (1984).

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Appendix A: West Virginia Case Study

This case study is appended to illustrate the practical applications of identifying surface features that occur as a result of underground coal mining subsidence. This case study considers how surface features related to underground coal mining subsidence may manifest in two study areas in West Virginia: (1) the northern study area, which includes portions of Marshall, Wetzel, and Tyler counties, and (2) the southern study area, which includes portions of Kanawha and Boone counties (A1). Both areas have a history of longwall mining and room and pillar mining. The northern study area was chosen because it includes large areas crossed by some of the largest underground mines in West Virginia, sometimes greater than ten miles in length. LiDAR coverage that crosses known underground mines is limited to a swathe, measuring about .5 miles (.8 kilometers) wide by about 20 miles (30 kilometers) in length. The southern study area was chosen because there is abundant LiDAR coverage and considerably more mining has taken place than in the northern study area. Also, multiple coal seams are commonly mined in stratigraphic succession in the southern study area, which typically results in greater subsidence at the surface than when only one seam is mined. In contrast, in the northern study area, large-scale mining operations are mining only the Pittsburgh coal seam, which is often located upwards of 1000 feet (300 meters) below the surface. This case study reviewed LiDAR, Pictometry and Google Earth imagery in areas above active and abandoned underground mines within each study area. The purpose of this case study is to compare and contrast surface features related to underground mining subsidence between the northern and southern West Virginia study areas. A brief history about coal mining in West Virginia, descriptions of regional geologic conditions, and observations, are provided below. This case study also gives discussion to what was learned during the course of the study and suggests possible future work.

Coal History

Underground coal mining in West Virginia has been ongoing since about the early 1800's (West Virginia Office of Miners' Health Safety and Training, 2013). After the Civil War, coal production in the United States grew at an accelerated rate in order to provide coke for use in smelting steel (Gray and Bruhn, 1984). Coal has been the largest source for generating electricity in the United States for over 60 years (U.S. Energy Information Administration). West Virginia is the second largest coal producing state next to Wyoming (U.S. Energy Information Administration), much of which comes from underground mines. In 2012, West Virginia produced an estimated 120 million short tons of coal, amounting to about 12% of total coal production in the United States (U.S. Energy Information Administration). At least 11% of the surface area in West Virginia is underlain by active or abandoned mines (A2), which indicates a vast potential for observing surface features related to mining subsidence.

Northern West Virginia Geologic Setting

The geology of the northern West Virginia study area is summarized by Cardwell (1979): The upper 2000 feet of the stratigraphy in the northern West Virginia study area is composed of Pennsylvanian to Lower Permian sedimentary rocks (A3). The top 500 feet largely consists of red shale (A3). The beds are gently dipping with dips that typically do not exceed 100 feet per mile. The gently dipping beds form northeast to southwest trending folds. The economically viable coal of the Pittsburgh coal seam is mined at a depth between 200 to 1200 feet below the ground surface (UMWA, 2013). The Pittsburgh seam is the only seam being mined for large-scale mining operations in the northern study area.

Based on review of DEMs, and aerial photography, the topography in the northern study area appears “stair-stepped” as a result of alternating resilient and weak rocks. The “steps” are variable in size but are typically on the order of about 10 feet (3 meters) high and up to tens of feet long. Landslides are a common occurrence on the steep hillslopes of the northern study area and range from small translational landslides to landslide complexes measuring up to several hundreds of feet wide by hundreds of feet long.

Southern West Virginia Geologic Setting

The southern West Virginia study area includes portions of Kanawha and Boone counties. Middle Pennsylvanian-age sandstones, shales, siltstones, and coals of the Kanawha formation are present throughout the study area (Martino, 1996; A4). The Kanawha formation measures about 1200 feet (400 m) thick at its type location in Kanawha County and thickens to about 2000 feet (600 m) thick along its southern outcrop extent (Arndt, 1979; Repine et al., 1993). The paleogeography of the southern study area was likely dominated by fluvial-deltaic environments that prograded northwestward from the rising Appalachian Mountains (Home and Ferm, 1978; Donaldson et al., 1985). The economically viable coals in the southern study area were deposited in these fluvial-deltaic environments (Martino, 1996). The sedimentary rocks that make up the Kanawha formation are the result of multiple sequences of transgression-regression during the Pennsylvanian (Martino, 1996).

The terrain in the southern study area is made up of steep slopes that are dissected by stream channels. The dissected topography results in local relief of about 500-1000 feet. Based on review of DEMs, the hillslopes have a subtle, stair-stepped appearance throughout the southern study area, presumably as a result of alternating layers of weak and resilient rocks. Similar to the northern study area, landslides are a common occurrence due to the presence of steep slopes and weathered materials.

Remote Investigation, Northern Study Area

The LiDAR coverage within the northern study area crosses the location of both active and abandoned underground mines. No room and pillar-related subsidence features were observed in the northern study area (i.e., sinkholes and subsidence troughs). Given the depth of mining in this area, shallow features are not expected. Despite LiDAR coverage spanning areas of known longwall mining, no surface features were observed from LiDAR that coincide with this type of mining, i.e., subsidence basins, linear cracks/fissures, stream heave, etc. The fact that no surface features were observed from LiDAR in the northern study area does not indicate the area is devoid of subsidence morphology. In fact, the opposite is known to be true. For example, the heave feature located at the unnamed tributary of Wheeling Creek (Figure 17) is known to be consistent with longwall mining-related subsidence, though no LiDAR coverage was available for this site.

Remote Investigation, Southern Study Area

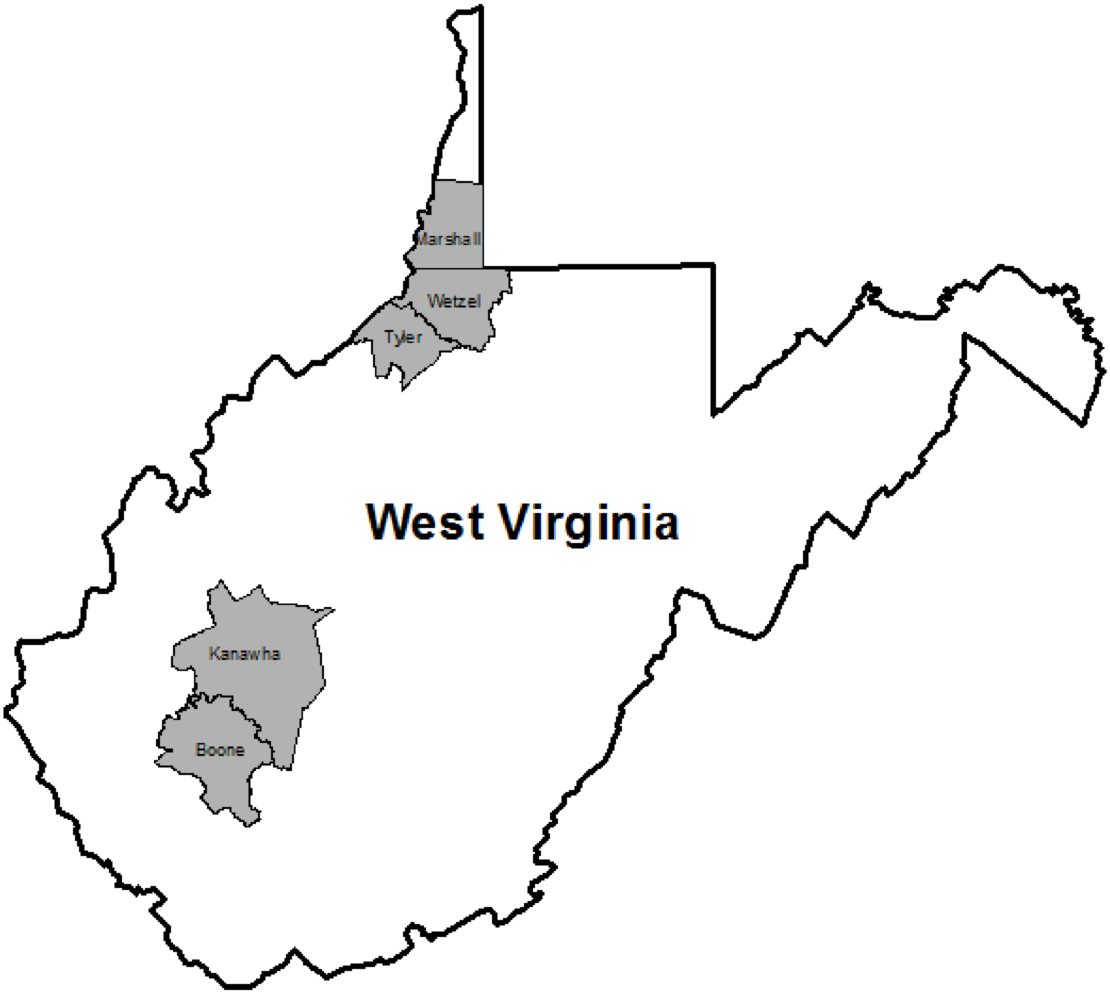
An abundance of cracks/fissures are observed throughout the southern study area (Figure 21). Many cracks/fissures cross the fall line and cut across ridges. The strike of the cracks/fissures appears random. However, statistical analysis of the strike of these features needs to be conducted in order to discern any regional pattern. Many of the cracks/fissures measured upwards of several hundreds of feet long by about 10 to 15 feet (3.0 to 4.5 meters) wide. In many cases a set of linear sinks was located in-line with these large cracks/fissures. However, isolated depressions were also commonly observed in hillshade, possibly representing sinkholes. The resolution of the LiDAR was typically about 3-foot (1 meter) horizontal resolution in the southern study area, compared to the 1-foot (.3 meter) horizontal resolution in the northern study area. Many examples of possible mine portals were observed throughout the southern study area.

Discussion

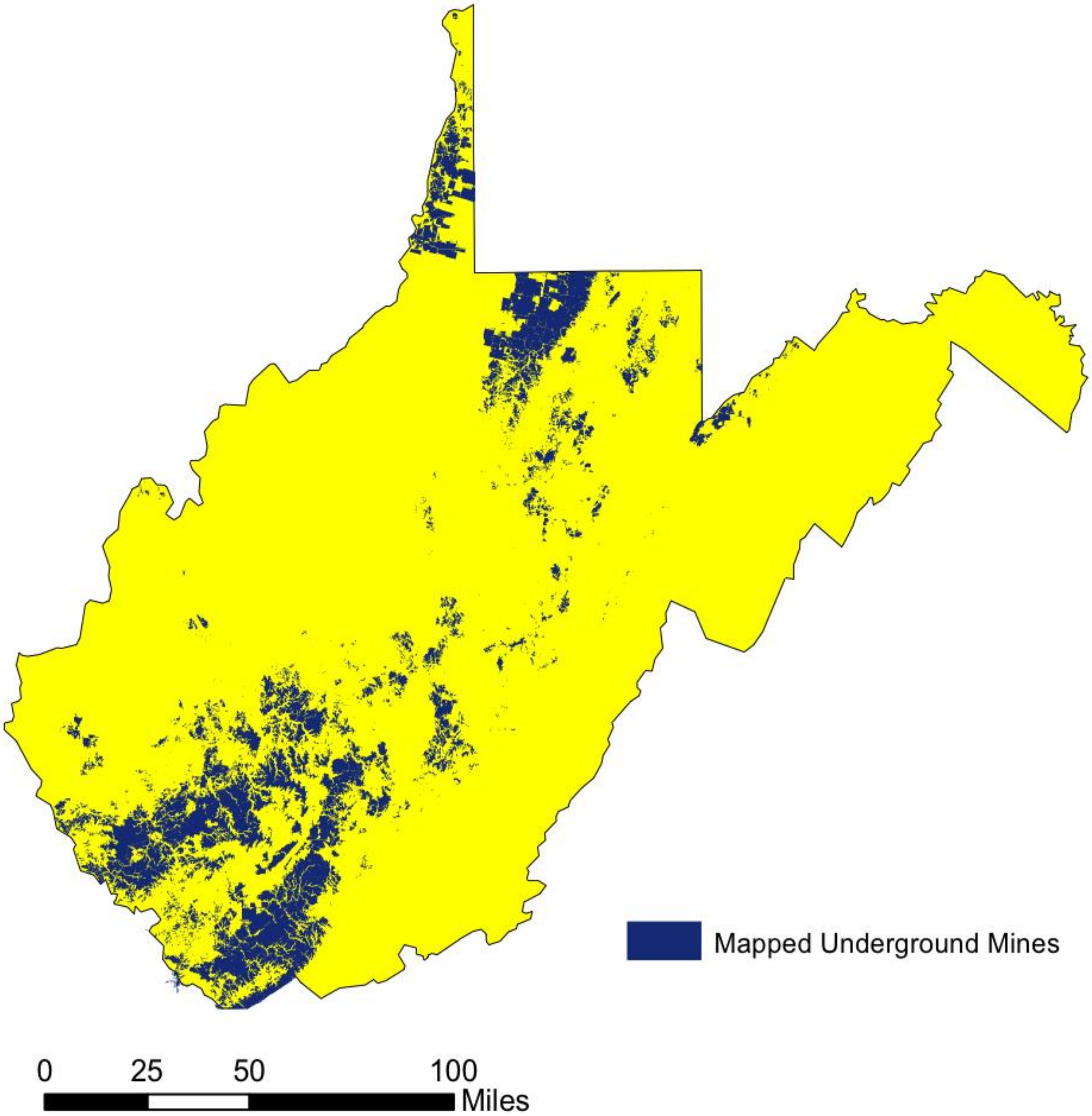
The northern study area has limited LiDAR availability and, based on my review, the geologic and mining conditions are unfavorable for observing subsidence remotely. Based on my review of LiDAR, Pictometry and Google Earth imagery, the southern study area is more favorable for observing mining-related subsidence remotely. Possible reasons for the difference in observed surface features between the two study areas may be related to differences in mining history and practice and/or geologic differences such as lithology, regional fracture networks, and in-situ stresses. For example, in northern West Virginia the Dunkard Group is largely composed of shales that may not readily transfer cracks to the surface as a result of strains being accommodated along bedding planes. Conversely, the thick beds of sandstone in the southern West Virginia coalfields may fracture massively and result in large fractures that cut across the fall line (Figure **19** and Figure 20).

Several possible causes exist that may attenuate or possibly obliterate subsidence-related morphology at the ground surface in the northern (and southern) study area(s). For example mining companies may mitigate surface subsidence by filling in cracks or restoring stream flow. Erosion and land use may alter the surface expression of subsidence features. Also, the resolution of the LiDAR in the northern study area, while at the 1-foot resolution, may still be lower than what is needed to observe some subsidence-related features. Further investigations should take place in the northern study area, particularly as LiDAR becomes available. The manner in which known subsidence features manifest on LiDAR may then be better understood, such as the example of stream heave at the unnamed tributary of Wheeling Creek.

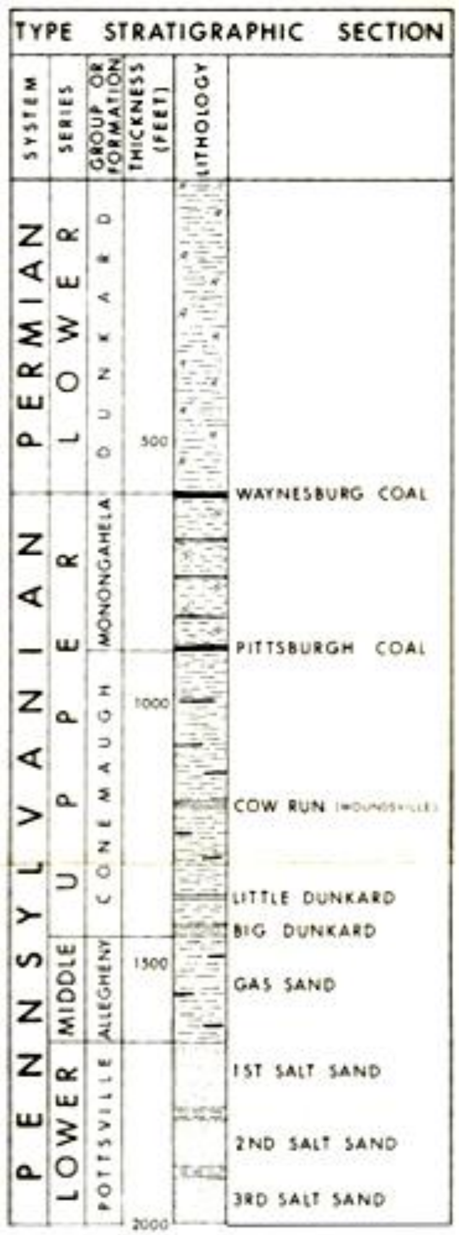
Despite the lower resolution LiDAR in the southern study area, many possible subsidence-related features were observed. Several reasons exist that may explain this difference. For example, mining of multiple coal seams above one another increases the net surface subsidence as a result of more material being removed. Also, thick sandstone units are present at the surface throughout the southern study area, which may transmit cracks more readily to the surface. It is possible that the LiDAR-identified possible subsidence features in the southern study area are simply naturally occurring discontinuities within the rocks. However, given the significant amount of mining that has occurred in the area, this is highly unlikely. Statistical studies could be conducted in the southern study area to investigate the amount of cracks located within and outside of the lateral limits of underground mines. Any studies investigating the presence of cracks should consider appropriate buffered distances, taking into account the angle of draw and depth of mining. It would also be interesting to investigate the orientation of cracks within the southern study area to determine if these features are controlled by any regional pattern.



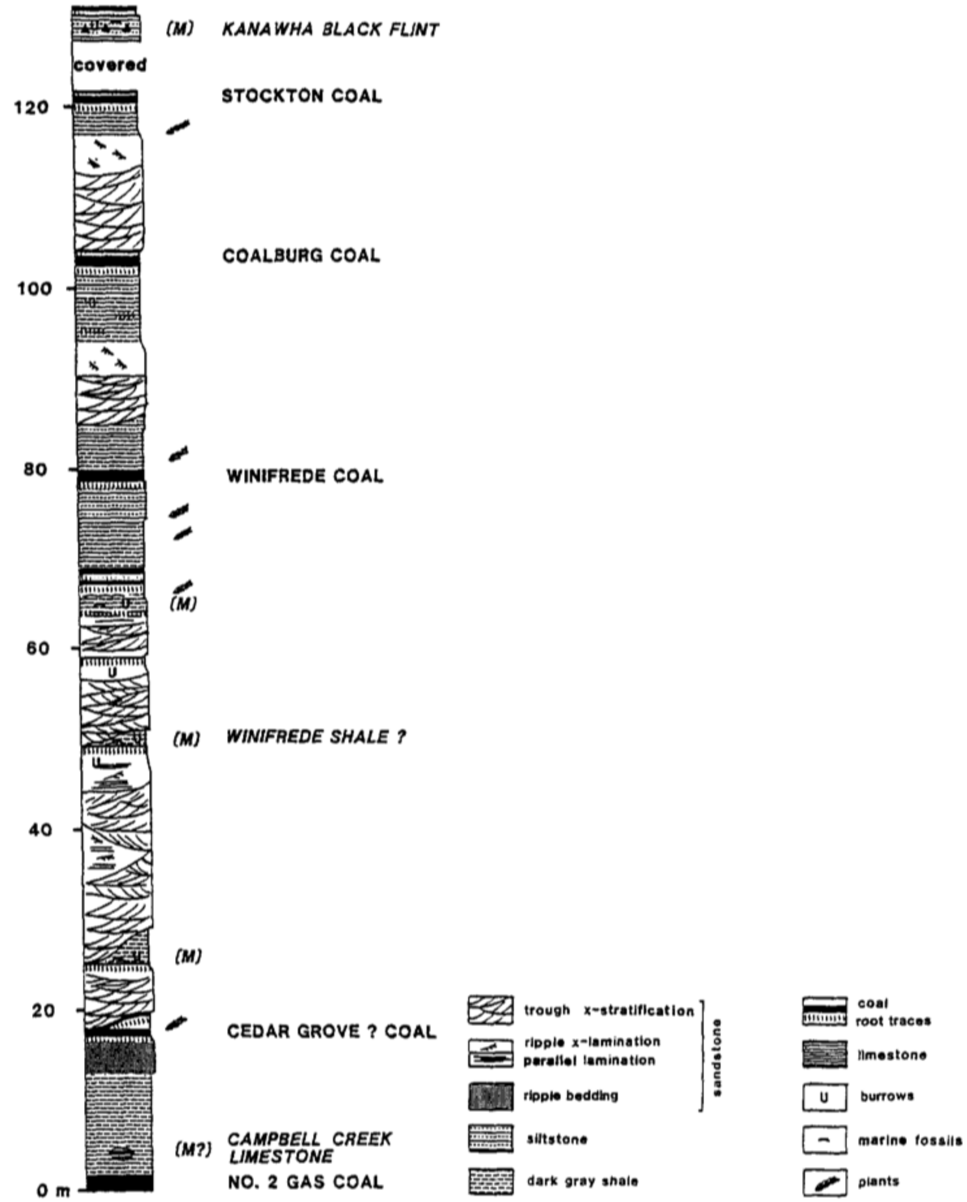
A1. West Virginia study areas. Map created by Clay Johnson, state and county data from Esri.



A2. Map of West Virginia showing the ground surface limits of underground mines. Created by Clay Johnson. State data from Esri; underground mine data from West Virginia Geologic and Economic Survey.



A3. Stratigraphic section for Marshall, Wetzel, and Tyler Counties, West Virginia. Modified from Cardwell (1979).



A4. Stratigraphic column of an outcrop located within the southern study area. Modified from Martino (1996).