



# **EXHIBIT 60E SUBSIDENCE EVALUATION FOR THE SOUTHERN PANELS, APACHE ROCKS WEST, & SUNSET TRAIL MINING AREAS**

## **PREPARED FOR:**

Mountain Coal Company, LLC.  
West Elk Mine  
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**Wright Water Engineers, Inc.**

**Revised December 2020**

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**SOUTHERN PANELS, APACHE ROCKS WEST,**  
**& SUNSET TRAIL MINING AREAS**

**MOUNTAIN COAL COMPANY, LLC**  

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**WEST ELK MINE**

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**Revised December 2020**

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## DEFINITION OF SYMBOLS

<b><u>Symbol</u></b>	<b><u>Definition</u></b>	<b><u>Dimensions</u></b>
$S$	Vertical Displacement (Subsidence)	$L$
$S_m$	Maximum Vertical Displacement ( $S_m=a \cdot t$ )	$L$
$S/S_m$	Ratio of Vertical Displacement to Maximum Vertical Displacement	$L/L$
$S_h$	Horizontal Displacement	$L$
$t$	Coal Extraction Thickness	$L$
$a = (S_m/t)$	Subsidence Factor	$L/L$
$a_{cp}$	Subsidence Factor Above Chain Pillars	$L/L$
$S_{cp}=a_{cp} \cdot t$	Maximum Subsidence Above Chain Pillars	$L$
$d$	Overburden Depth	$L$
$S_m/d$	Ratio of maximum vertical displacement to overburden depth	$L/L$
$W_{cr}$	Critical Extraction Width	$L/L$
$W/d$	Mining Width to Overburden Depth Ratio	$L/L$
$M$	Tilt (Slope)	$L/L$
$M_m$	Maximum Tilt	$L/L$
$C$	Curvature, the reciprocal of Radius of Curvature	$rad/L (1/L)$
$C_m$	Maximum Curvature	$rad/L (1/L)$
$E$	Horizontal Strain (+) is Positive, (-) is Negative	$L/L$
$E_m$	Maximum Horizontal Strain	$L/L$
$\phi$	Angle of Draw	Degrees
$B$	Break Angle	Degrees
$\beta$	Angle of Major Influence	Degrees
$r$	Radius of Major Influence	$L$

## DEFINITION OF TERMS

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**South of Divide Mining Area.** The mining area encompasses the E-seam longwall panels located primarily in Sections 32, 33, and 34 of Township 13 South, Range 90 West of the 6<sup>th</sup> Principal Meridian, and Sections 3, 4, and 5 of Township 14 South, Range 90 West of the 6<sup>th</sup> Principal Meridian. The panels are identified as E1 to E9.

**Dry Fork Mining Area.** The mining area encompasses the extension of the E-seam longwall panels from the South of Divide Mining Area into the Dry Fork Mining Area. The area is located primarily in Section 35 of Township 13 South, Range 90 West of the 6<sup>th</sup> Principal Meridian and Sections 1 and 2 of Township 14 South, Range 90 West of the 6<sup>th</sup> Principal meridian. The panels are identified as E2 to E6.

**Southern Panels Mining Area.** The mining area includes the E-seam longwall panels originally included in the South of Divide Mining Area and some of which were extended into the Dry Fork Mining Area (E1 to E9, as above). The Southern Panels mining area also includes the B-seam longwall panels (B26 to B29) that will underlie Southern Panels E1 to E5. Throughout this exhibit, this term will be used to identify what was formerly referred to as the South of Divide and Dry Fork mining areas.

**Apache Rocks West Mining Area.** The Apache Rocks West panels refer to the three western panels in the Apache Rocks Mining Area (as defined in the original Exhibit 60), which are located in Sections 28, 29, and 30, Township 13 South, Range 90 West, of the 6<sup>th</sup> P.M. Both B- and E-seam longwall mining will occur in this area.

**Sunset Trail Mining Area.** The mining area encompasses the E-seam longwall panels located primarily in Sections 10, 11, 14, and 15 of Township 14 South, Range 90 West of the 6<sup>th</sup> Principal Meridian. The panels are identified as SS1 through SS4.

**Critical Mining Width.** The width of a mining panel necessary for maximum subsidence to occur; the length of the panel must also be greater than, or equal to, critical panel width for maximum subsidence to occur. Critical width ( $W_{cr}$ ) commonly ranges from 1.0 to 1.4 times the mining depth ( $d$ ).

**Subcritical Mining Width.** The width of a mining panel less than critical width (i.e., less than 1.0 to 1.4 $d$ ).

**Supercritical Mining Width.** The width of a mining panel greater than critical width.

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## **1.0 INTRODUCTION**

This exhibit describes longwall panel subsidence processes that have been observed from studies above longwall panels mined in Mountain Coal Company, LLC's (MCC) West Elk Mine and from other similar operations and studies. The subsidence information obtained from longwall mining to date in the West Elk Mine has been used to project subsidence processes, amounts, and effects to the Southern Panels, Apache Rocks West, and Sunset Trail mining areas within MCC's permit and affected area boundaries. This document is intended to comply with the Colorado Division of Reclamation, Mining and Safety (DRMS) Regulations for Coal Mining, as revised September 14, 2005, under Section 2.05.6, Mitigation of the Impacts of Mining Operations.

This report was updated by Tetra Tech September 2007 and was added to the approved permit document as Exhibit 60E to include the Dry Fork lease mining area with the longwall mining area of the South of Divide coal leases within the permit area. Since these areas are being mined together, it is logical to consider them together in one report. Most of the report is "as contained" in the Exhibit 60B prepared by C. Richard Dunrud of Wright Waters Engineers, Inc. (WWE) in March 2006 for the South of Divide mining area. Maximum projected mining was planned into the Dry Fork mining area in E-seam longwall panels E2 to E6 to the east permit area boundary and under the upper areas of Dry Fork, a tributary to Minnesota Creek, and the upper areas of Deep Creek. Panels E1, E7, E8, and E9 remain within the boundaries of the South of Divide mining area previously evaluated.

WWE further updated Exhibit 60E to reflect the maximum projected areal extent of potential longwall mining within the potentially mineable coal reserves of the Dry Fork mining area. MCC's projected E-seam mining has not changed and continues to reflect the best available information (including exploration and actual E-seam mining data) regarding the mineable E-seam coal. However, during ongoing longwall panel development, additional mineable coal has been and may be found to exist beyond the projected E-seam longwall panel shown on permit Map 51. If mineable coal is found beyond the projected longwall panel and is within the Maximum Projected Areal Extent area, MCC may continue mining within this area.

The 2015 update addressed a revised longwall panel layout in the two-seam mining area known as the Apache Rocks West panels that was addressed in the original Exhibit 60 (May 1995). In addition, the update evaluated the subsidence due to two-seam mining in the Southern Panels mining area as shown in Figure 1. The 2018 update evaluated the subsidence associated with longwall mining of the E-seam in the Sunset Trail mining area. WWE analyzed the proposed layout for longwall panels SS1 through SS4 as shown in Figure 1. The 2020 update was performed



in order to reflect the most current information regarding the layout for the Sunset Trail longwall panels and panel E14 and the projected overburden thicknesses in these areas.

The geologic and mining conditions are consistent throughout the Southern Panels, Apache Rocks West, and Sunset Trail mining areas (Agapito, 2005). Therefore, no change was needed in the subsidence model prepared by Dunrud and predictions for subsidence over longwall panels in the South of Divide mining area are considered to also be applicable for the Dry Fork, Apache Rocks West, and Sunset Trail mining areas.

## 2.0 MINING METHOD

The longwall mining method has and will continue to be utilized in the Southern Panels, Apache Rocks West, and Sunset Trail mining areas. The projected longwall panels designs are similar to the B-seam and E-seam longwall panels mined to date in the West Elk Mine, where subsidence measurements were used to obtain the baseline data that were used in this report. A range of 8 to 14<sup>1</sup> feet of coal will be extracted from the E-seam in the Southern Panels mining area. The four longwall panels in the Sunset Trail mining area (SS1 through SS4) are proposed to have an extraction thickness ranging from 9 to 14 feet. The extraction thicknesses are projected based on exploration drillhole data; actual thicknesses may vary depending on mining conditions encountered, but will not be greater than 14 feet.

E-seam longwall panels E1 to E8 were approximately 1,080 feet wide<sup>2</sup> and extended up to approximately 15,000 feet in length. Panel E9 is projected to be 1,080 feet wide and approximately 3,200 feet long. Panel E14 is projected to be 1,080 feet wide and approximately 3,300 feet long. The longwall panels will be mined by the retreat longwall mining method. Panels E1 to E8 were longwall mined from east to west as panel E14 will be. Panel E9 is planned to be longwall mined from south to north.

The trend of panels E1 to E8 is approximately N80°W. Projected panel E9 trends roughly N10°E and E14 trends approximately N60°W. The overburden depth above the longwall panels E1 to E4 ranged from roughly 375 to 1,800 feet, whereas, the overburden depth for longwall panels E5 to E8 ranged from approximately 500 to 1,800 feet. The overburden above the longwall panel blocks of E9 and E14 ranges in thickness from approximately 260 to 740 feet.

B-seam mining in the Southern Panels mining area will occur in panels B26 to B29, and will follow the same orientation as the overlying previously mined E-seam longwall panels. The longwall panels are projected to be approximately 1,080 feet wide with lengths varying from 11,500 feet up to 14,800 feet, and mining thicknesses from 9 feet up to 14 feet.

In the original Exhibit 60 (May 1995), MCC anticipated two-seam mining in the B- and E-seam in the Apache Rocks West mining area. MCC has already mined the B-seam in this area (B12, B13, and B13-A); however, the layout of the E-seam panels (E10 to E12) has shifted from being stacked over the B-seam panel to being offset. Panels E10 to E12 are projected to be approximately 850 to 1,080 feet wide and vary in length from approximately 3,800 feet to 5,300 feet. The mining thickness is anticipated to vary from 10 to 14 feet.

E-seam mining in the Sunset Trail mining area will occur in Panels SS1 to SS4 as shown in Figure 1. Panels SS1 to SS4 are projected to be approximately 1,080 feet wide with maximum lengths ranging from approximately 7,200 feet up to 9,400 feet. The panels are and will be oriented parallel to panels E1 to E8. The mining thickness is anticipated to vary from 10 to 14 feet. The

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<sup>1</sup> Practically speaking, the maximum mining height with the current longwall is 13.5 feet; however, WWE is using 14 feet in our analysis to be conservative, except with the computer modeling.

<sup>2</sup> All of the panels discussed in this exhibit are approximately 1,080 feet wide. When evaluating subsidence, a total extraction width of 1,120 feet was used to include the entries parallel and adjacent to the longwall panel block.

overburden above panels SS1 to SS4 ranges in thickness from approximately 280 feet up to 1,300 feet.

All longwall panels are planned to be separated by two or three rows of chain pillars. The pillars on both the headgate and tailgate sides of the panels are typically on centers of about 125 feet wide by 200 feet long. The headgate for the adjacent panel becomes the tailgate panel on the subsequent panel. These mine plans and pillar designs may change as mining experience, geological-geotechnical conditions, and/or mine operational procedures dictate. This exhibit focuses on subsidence projections over the mined longwall panels.

### 3.0 FACTORS INFLUENCING SUBSIDENCE

Subsidence may be influenced by the local geology in the following ways:

1. Geologic structure. Attitude of the bedrock, faulting, and jointing may affect the mine layout and mining method employed. In steeply dipping, faulted coal beds, for example, a mine layout and method, such as room-and-pillar or limited panel-pillar, may be required. Joints often control the way in which the roof rocks break, cave, and fracture, both underground and at the surface during mining and subsidence. In relatively flat-lying, unfaulted coal seams like the Southern Panels, Apache Rocks West, and Sunset Trail mining areas, there is latitude to develop the most efficient layout and method to recover a maximum amount of the coal resource with a minimum of impact.
2. Strength and behavioral properties of the rocks. These properties control the amount and rate of subsidence. Strong, brittle sandstones and siltstones tend to break and cave in large blocks on the mine floor. The bulking factor is greater for strong rocks than it is for soft, weak rocks. The greater bulking factor of strong, caved material commonly reduces the height of caving and the subsidence factor compared to soft, weak rocks. Conversely, the height of fracturing often is greater for strong, brittle rocks than it is for soft, weak rocks.
3. Stratigraphic sequence. The stratigraphic distribution of rock units (stratigraphic sequence) influences the effects of mining and subsidence. For example, strong and brittle sandstones in the mine roof, as discussed above, can reduce the height of caving compared to shales, whereas sandstones in the fractured zone above the caved zone may increase the height of fracturing compared to shales. Conversely, the height of caving may be increased and the height of fracturing decreased where weaker shale and claystones occur in the fractured zone above the coal seam to be mined.

In addition, the lithology of the overburden rock may control the subsidence factor. The subsidence factor may be less where the overburden contains a greater proportion of thick, strong sandstones, and greater where the overburden contains thin, weak shales. In the Southern Panels, Apache Rocks West, and Sunset Trail mining areas, the first 200 to 300 feet of rocks above the E-seam consist primarily of siltstones, shales, claystones, local lenticular sandstones, and coal seams.

4. Moisture content. Wet or saturated conditions in the mine roof and overburden tend to reduce the bulking factor of the caved roof rocks. Therefore, the subsidence factor commonly is greater under wet conditions than it is in dry conditions. In general, the greater the saturation of the mine roof and overburden rocks, the greater the subsidence factor.

## **4.0 FIELD RECOGNITION OF SUBSIDENCE AND NON-SUBSIDENCE FEATURES ABOVE THE WEST ELK MINE**

Four different types of features are observed in the area above the West Elk Mine: 1) subsidence cracks and bulges, 2) construction cracks, 3) desiccation cracks, and 4) gravity-induced tension cracks. They can be distinguished easily in some areas—where, for example, no mining has occurred in that area. However, in other areas they may be difficult to distinguish, such as in areas that have been mined, but where conditions are also favorable for construction, desiccation, and/or gravity-induced tension cracks to occur.

### **4.1 Subsidence Cracks and Compression Features**

Subsidence cracks are open cracks that most likely occur in areas where the ground surface has undergone extension during subsidence processes. Cracks as much as 3.5 inches wide, for example, have been observed in sandstone outcrops at Apache Rocks where zones of maximum extension (or tension in rock mechanics terminology) occur. As discussed in Section 5.3.2, cracks close—and the underlying rocks become compressive—below the neutral surface (the boundary between tensile and compressive strain) of the rocks downwarping as a single unit. Therefore, any water located in cracks above the neutral surface is blocked from traveling downward into rocks in compression below the neutral surface.

Cracks in the zone of maximum tension occur approximately perpendicular to the orientation of the longwall mining faces (transverse cracks) and parallel to the orientation of the longwall mining panels (longitudinal cracks). The cracks commonly do not conform to such a precise pattern. As with other deformational processes in nature, crack orientation may be quite variable.

The transverse tension cracks that locally occur above the longwall mining face often have a dynamic history. They open when the longwall face moves beneath a particular area, and they close again when the longwall face moves out of the area of mining influence.

Longitudinal cracks occur above and roughly parallel to the edges of the longwall mining panel above the gateroad pillars and the haulageway (or beltway) pillars. Longitudinal tension cracks commonly remain open, particularly in areas above gate roads with a rigid-pillar configuration. The cracks may stay open or close in areas above gate roads with a combination rigid-pillar/yield-pillar configuration. However, as discussed in Section 5.3.2, it is unlikely that cracks will occur in colluvium and alluvium in the stream valleys of the Southern Panels and Sunset Trail mining area.

Compression features (bulges and warps) also occur above the longwall mining panels in areas where the ground surface undergoes compression in the subsidence process. The compression features, which occur toward the center of the mining panel in zones of maximum compression, are usually more difficult to recognize. They often are masked, or absorbed, by soil and colluvium, or are hidden in the brush and grass. They also may be indistinguishable from natural humps and mounds in the soil and colluvium.

## **4.2 Construction Cracks**

Cracks caused by construction activities are common on the banks of newly constructed roads and drill pads. These cracks are caused by the bulldozer and related differential compaction during construction activities. The cracks are most noticeable where fractured and weathered bedrock is encountered. However, this type of cracking also occurs in soil and colluvium where roots of brush and trees are pulled out of the road cut by the bulldozer. In contrast to subsidence cracks, construction cracks occur in a continuous zone where weathered and/or fractured bedrock is encountered during road construction.

Construction cracks may be confused with subsidence cracks, particularly where mining has occurred in the area, and where local bedrock is weathered and fractured, or where brush and trees have been ripped out of soil and/or colluvium during the construction process. The most diagnostic features of construction cracks are that they 1) have a less regular pattern, 2) are related to the material they occur in, and 3) they lack of any spatial relationship to the underlying longwall mine geometry.

## **4.3 Desiccation Cracks**

Desiccation cracks tend to occur in claystones and siltstones of the Mesaverde and Wasatch Formations in the area above the West Elk Mine, particularly where the rocks are weathered to clays and silts. The process of desiccation involves the shrinking of the clays and silts after a dry period that follows a wet period, when the material swells (the shrink/swell process).

Desiccation cracks can often be recognized by their irregular, branching and diverging pattern—less regular than typical subsidence cracks. Some of the largest desiccation cracks in the area above the West Elk Mine were observed in clays of the Barren Member of the Mesaverde Formation in the Horse Gulch-Minnesota Reservoir area and in the weathered claystones of the Wasatch Formation on West Flatiron, before there had been any mining. The larger, more regular desiccation cracks and construction cracks may be confused with subsidence cracks in areas where mining has occurred. However, transverse and longitudinal subsidence cracks have a definite spatial relationship to the longwall mining panel causing the cracks.

## **4.4 Pseudo Subsidence Features (Gravity-Induced Tension Cracks)**

Cracks have been observed on high, steep ridges, near cliffs, and in landslides, in the Box Canyon and Apache Rocks mining areas. These cracks looked very much like subsidence cracks, but could not have been, because no mining had been done when they were observed. A good example of a gravity-induced crack is the extensive crack that Dunrud observed on the narrow ridge of West Flatiron in August 2002. This crack was as much as 3.5 in wide and 150 feet long. This was not a mining-related crack because no mining had occurred in the area. The possibility of gravity-induced cracking in the rugged country above planned mining activities in the West Elk Mine is a good reason to perform baseline studies of the area prior to any mining so that these features can be documented.

Cracks and bulges caused by landslides are other types of gravity-induced features that may appear to be related to subsidence, particularly in areas that have been, or are being, undermined.

However, landslide-induced features are related to the geometry of the landslide rather than the mine geometry. For example, cracks are most common in the upper area of a landslide, whereas, bulges are most common in the lower area of the slide. This spatial and geometric relationship to a landslide footprint on steep, unstable slopes, rather than the mine geometry can usually be used to differentiate between gravity-induced and mine-induced surface features.

## **5.0 SUBSIDENCE PREDICTION BASED ON LONGWALL MINING AT WEST ELK MINE**

Subsidence, as it relates to longwall mining, is defined herein as the local downward displacement of the surface and overburden rock in response to mining under the influence of gravity. For purposes of describing subsidence effects on overburden material and the ground surface, subsidence can be divided into four zones (Figure 2): 1) caved zone, 2) fractured zone, 3) continuous deformation zone, and 4) near surface zone.

### **5.1 Caved Zone**

As coal is extracted and a void is produced, the roof rocks break along bedding planes, joints, and fractures and fall to the mine floor (Figure 2). Rotation of the caved debris occurs during the fall so that the caved fragments tend to pile up in a random fashion. This caved zone, according to Peng (1992, p. 1-2) occurs for the first 2 to 8 mining (or coal extraction) thicknesses ( $2t$  to  $8t$ ) in the roof rocks (for example, if  $t=12$  feet, the caved zone would range from 24 to 96 feet [ $2t$  to  $8t$ ]). According to Wendell Koontz, former senior geologist at West Elk Mine, this caved zone averages about  $2.5t$  for longwall mining of the B-seam in the West Elk Mine. This includes the Apache Rocks and Box Canyon mining areas (Koontz, oral communication March 2004).

Based on the stratigraphic and lithologic information obtained from drill holes in the Southern Panels and Sunset Trail mining areas, the rocks consist of a greater proportion of shales, siltstones, and claystones than are present in the Apache Rocks and Box Canyon mining areas. The height of the caved zone is therefore projected to range from  $2t$  to  $5t$ , depending on water conditions encountered and on specific roof lithology. In a dry environment, where lenticular sandstones comprise the E-seam roof, the caved zone will be closer to  $2t$ . In a wet environment where soft shales and claystones occur in the roof, however, the caved zone will likely be closer to  $5t$ . The average height of the caved zone is projected to average  $3t$  in the Southern Panels and Sunset Trail mining areas.

### **5.2 Fractured Zone**

A zone of fracturing and local separation along rock bedding planes and joints occurs above the zone of caving (Figure 2, Enlargement 1). In this zone, which is transitional to the underlying caved zone, lateral and vertical constraints in the adjacent overburden strata and the caved rocks below prevent further large displacement or rotation of the fractured rock. Displacements in the fracture zone and severity of fracturing tend to decrease upward as lateral and vertical confining stresses increase.

Based on width and conductivity of fractures Peng (1992, p. 143) states that the upper one-third of the fractured zone (in terms of height) has only minor fractures with little potential for water conductivity. In the lower two-thirds of the fractured zone, water conductivity commonly increases progressively downward.

Compression arches (arcuate zones of compressive stress) commonly develop, or partially develop, above the mining panels. These arches temporarily transfer overburden stresses to the panel barrier or chain pillars and to the caved gob and the mining face (Dunrud 1976). Stresses



temporarily increase in the zones of these compression arches. However, the arches in a given area commonly move upward and dissipate as longwall mining is completed in that area. Arches may not dissipate where the room-and-pillar mining method is used, because pillars and stumps left after mining can prevent dissipation of the compression arches. The overburden rocks affected by the arches are temporarily subjected to increased stress and strain as the arches move upward. In longwall mining areas, this increased stress and strain commonly are less than in room-and-pillar mining areas because stresses are relieved as the arches move upward and dissipate.

Peng (1992, p.4) reports that the combined height of the zone of caving and fracturing ranges from 20t to 30t, and that the height of the fractured zone is greater for hard, strong rocks than for soft, weak rocks.

The height of the zone of fracturing is a function of lithology and layer thickness, according to Peng (1992, p. 6-8). For example, the zone of fracturing commonly is higher for strong, thickly-bedded, brittle sandstones than it is for thinly layered, soft, shales and claystones. Liu (1981) reports ranges of heights of the zone of fracturing for various rock types as follows:

1. Heights of 20t to 30t are reported in strong brittle rocks, such as siliceous sandstones and limestones; a value of 28t was reported for overburden containing 70 percent sandstone. Also, because of hardness, fractures do not close as readily in brittle rocks as they do in soft rocks during recompression.
2. Heights of 9t to 11t are reported where all the rocks consist of soft shales and claystones. The fractures also commonly close again under stresses associated with static conditions, and become impermeable again.

Considering the lithology of the areas, Mr. Koontz estimated that 10t to 20t was a good projection for the height of fracturing in the Apache Rocks and Box Canyon mining areas. However, a projected fracture height of 30 times the coal extraction thickness (30t) may locally occur (Koontz, oral communication March 2004).

Within the Southern Panels and Sunset Trail mining areas, the fracture zone may become less continuous in the caved zone with increasing height because of the alternating sequence of harder and brittle rocks and softer and yielding rocks. The height of the fracture zone, therefore, will likely be less—by possibly 10 to 20 percent—than the height predicted for the Apache Rocks and Box Canyon mining areas because of the presence of more shale above the E-seam mining in the Southern Panels and Sunset Trail mining areas. Fractures near the top of the caved zone, therefore, will likely become less continuous with increasing height in the zone of fracturing.

The maximum height of fracturing above longwall panels in the Southern Panels and Sunset Trail mining area is estimated to range from about 10t to 20t. This is near the mid-range of 9t to 30t as reported by Peng (1992, p. 7). This estimate may be conservative for the particular rock strata or lithology above the E-seam. When considering a conservative 10 percent reduction for the softer rocks overlying the E-seam, the effective height of fracturing in the Southern Panels and Sunset Trail mining areas is estimated to range from 9t to 18t.

In areas of two-seam mining, it is possible for the heights of the fractured zones to become cumulative as the height of fracturing from the underlying B-seam could extend up to the E-seam. This potential exists in the Apache Rocks West and Southern Panels mining areas. However, this phenomenon would not increase the height of fracturing above the E-seam, which would govern the potential for near-surface impacts.

Also, with increasing height in this zone, and as lateral and vertical constraints increase, fracturing that could impact water bearing zones will tend to occur more in zones of convex upward curvature, along separated bedding planes toward the center of the panel, and along local cracks in zones of convex downward curvature (Figure 2). Fracturing within the expected zone of fracture may cease completely where soft shales and claystones occur as alternating sequences with sandstones.

Drainage into the fractured formations, however, may cease after mining is complete and any water bearing zones present may be restored. This is particularly likely in the upper part of the fractured zone in shale sequences between sandstone layers, once subsidence is completed and the separated beds re-compress and close in response to overburden load (Figure 2). Although very few water bearing zones have been encountered, evidence of restored water levels has been measured and reported in some wells in the West Elk Mine subsidence monitoring area after B-seam mining and subsidence were complete.

### **5.3 Continuous Deformation Zone and Near Surface Zone**

These two zones are discussed together because the ground surface is where nearly all measurements are made that monitor subsidence processes active in the zone of continuous deformation.

The near surface zone, which typically consists of weathered bedrock, colluvium, alluvium, and soil a few feet to a few tens of feet thick, may deform differently than the underlying bedrock (Figure 2). Field studies by Dunrud indicate that near-surface colluvium and alluvium, which consist of predominantly clay and silt, can undergo significantly more extension without rupturing than can the underlying material. In both the Somerset, Colorado and Sheridan, Wyoming field study areas, colluvium and alluvium 5 to 10 feet thick were observed to cover cracks as much as 10 to 14 inches wide so that there was no indication of the underlying fractures.

The zone of continuous deformation, which is transitional to the overlying near-surface zone and also to the underlying zone of fracturing, undergoes differential vertical lowering and flexure as laterally-constrained plates (in three dimensions) or beams (in two dimensions). With flexure, shear occurs at the boundaries of rock units with different strength and stiffness, characteristics, such as sandstones and shales. Zones of tension above the neutral surfaces of a rock unit, for example, become compressive above the boundary with another rock unit and below its neutral surface (Figure 2, Enlargement 2). Any cracks, therefore, which occur in the tension zone of a rock unit, terminate at the neutral surface, because the unit is in compression below this point.

### 5.3.1 Vertical Displacement, Tilt, and Horizontal Strain

Differential vertical lowering of the continuous deformation and near surface zones causes vertical displacement (S), tilt (M), and horizontal strain (E). In flat or gently sloping terrain (slopes less than about 30 percent), surface profiles of subsidence depressions are similar to flexure of fixed-end, laterally constrained beams. Tensile stresses are present in areas of positive curvature, which become zero downward at the neutral surface, then reverse to compressive stresses below the neutral surface.

In flat or gently sloping terrain, vertical displacement typically increases inward from the limit of the subsidence depression, is half the maximum value at the point of inflection, and is maximum in the middle of the depression (also called subsidence basin or subsidence trough). Tilt increases inward from the margin of the depression to a maximum at the point of inflection and become zero again at the point of maximum vertical displacement (Figure 3). Maximum values of tilt, curvature, and strain, discussed herein, apply only to slopes less than about 30 percent; values may be greater on slopes steeper than 30 percent.

Positive curvature (convex upward) and horizontal tensile strain increase inward from the margin of the depression to a maximum about midway between the depression margin and the point of inflection and decrease to zero again at the point of inflection. Negative curvature (concave upward) and compressive horizontal strain increase inward from the point of inflection to a maximum about midway between the point of inflection and the point of maximum vertical displacement and decrease to zero again at the point of maximum vertical displacement.

#### 5.3.1.1 Maximum Vertical Displacement (Subsidence)

The following range of vertical displacements (subsidence values) are projected for the Southern Panels, Apache Rocks West, and Sunset Trail mining areas, based on the baseline data obtained from subsidence measurements above the B-seam longwall panels 1NW, 2NW, and 3NW (Figure 4, Table 1) and E-seam longwall panels E1 to E3 at West Elk Mine.

Southern Panels Mining Area: As noted above, the E-Seam longwall panels E1 to E8 were originally approved as part of the South of Divide mining area, and subsequently panels E2 to E7 were approved to extend into the Dry Fork mining area. To simplify the discussion of subsidence projections, the full-length panels are addressed as the Southern Panels E1 to E8. Similarly, the proposed B-seam panels in this area are referred to as the Southern Panels B26 to B29.

For purposes of the subsidence modeling evaluation, the overburden depth above the projected E-seam longwall centers ranges from approximately 370 to 1,800 feet. With a projected longwall panel width of approximately 1,080 feet, and assuming that the chain pillars (gate road pillars) are similar to those in longwall panel 17 of the Apache Rocks mining area, maximum subsidence (vertical displacement  $S_m = a \cdot t$ ) is predicted as follows (Table 2) for the Southern Panels mining area of panels E1 to E9 and E14:

- *Panels E1 to E9 and E14:* These panels range in width from subcritical to supercritical (width-to depth ratio (W/d) ranges from 0.76 to 2.92).

1. Maximum vertical displacement above the chain pillars ( $S_{cp}$ ) is expected to range from 0.9 to 2.7 feet (0.1 to 0.3t) where the extraction thickness is 9 feet, and from 1.4 to 4.2 feet (0.1 to 0.3t) where the extraction thickness is 14 feet.
2. Maximum vertical displacement above the mined longwall panels (subsidence,  $S_m = a \cdot t$ ) is projected to range from 5.4 to 7.2 feet (0.6 to 0.8t) where the extraction thickness is 9 feet, and from 8.4 to 11.2 feet (0.6 to 0.8t) where the extraction thickness is 14 feet.

Overburden depth above the projected B-seam longwall centers ranges from approximately 600 to 1,500 feet. With a projected longwall panel width of approximately 1,080 feet, maximum subsidence (vertical displacement  $S_m = a \cdot t$ ) is predicted as follows (Table 2) for the Southern Panels mining area of panels B26 to B29:

- *Panels B26 to B29:* These longwall panels range in width from subcritical to supercritical (width-to depth ratio ( $W/d$ ) ranges from 0.72 to 1.80).
  1. Maximum vertical displacement above the chain pillars ( $S_{cp}$ ) is expected to range from 0.9 to 2.7 feet (0.1 to 0.3t) where the extraction thickness is 9 feet, and from 1.4 to 4.2 feet (0.1 to 0.3t) where the extraction thickness is 14 feet.
  2. Maximum vertical displacement above the mined longwall panels (subsidence,  $S_m = a \cdot t$ ) is projected to range from 5.4 to 7.2 feet (0.6 to 0.8t) where the extraction thickness is 9 feet, and from 8.4 to 11.2 feet (0.6 to 0.8t) where the extraction thickness is 14 feet.

The E-seam panels E1 to E5 and B-seam panels B26 to B29 occur on top of one another, but are not stacked based on the current panel layout (Figure 1). Therefore, while the subsidence (vertical displacement  $S_m = a \cdot t$ ) of the two seams is additive, the maximum subsidence due to mining in each seam will not occur at the same location. The closer the alignment of the B-seam panel occurs in a stacked manner relative to the E-seam panels, the more additive the maximum subsidence will be.

The superposition of the subsidence curves for the longwall mining of the E-seam and B-seam indicates that the combined maximum subsidence will be roughly 80 percent of the sum of the maximums for each seam. To be conservative, the maximum for the two-seam mining will be estimated by summation of the maximums for each seam.

1. Maximum vertical displacement above the chain pillars ( $S_{cp}$ ) due to both E-seam and B-seam mining is conservatively estimated to be the summation of the subsidence for each seam, as the chain pillars for the E-seam and B-seam are nearly located on top of one another. For the two seam panel area, the maximum vertical displacement is estimated to range from 2.8 to 8.4 feet (0.1 to 0.3t) where the extraction thickness is 14 feet.
2. Maximum vertical displacement above the mined longwall panels (subsidence,  $S_m = a \cdot t$ ) for the B-seam and E-seam mining is projected to range from 10.8 to 14.4 feet (0.6 to 0.8t) where the extraction thickness is 9 feet, and from 16.8 to 22.4 feet (0.6

to 0.8t) where the extraction thickness is 14 feet. This estimate is only for the areas over panels E2 to E5 and B26 to B29.

*Apache Rocks West Mining Area:* Overburden depth above the projected E-seam longwall centers ranges from 400 to 1,100 feet. With a projected longwall panel width of approximately 1,080 feet, maximum subsidence (vertical displacement  $S_m = a \cdot t$ ) is predicted as follows (Table 3) for the Apache Rocks West mining area of panels E10 to E12:

- *Panels E10 to E12:* These panels range in width from subcritical to supercritical (width-to depth ratio ( $W/d$ ) ranges from 0.98 to 2.70).
  1. Maximum vertical displacement above the chain pillars ( $S_{cp}$ ) is expected to range from 1.0 to 4.0 feet (0.1 to 0.3t) where the extraction thickness is 10 feet, and 1.4 to 5.6 feet (0.1 to 0.3t), where the extraction thickness is 14 feet.
  2. Maximum vertical displacement above the mined longwall panels (subsidence,  $S_m = a \cdot t$ ) is projected to range from 6.0 to 8.0 feet (0.6 to 0.8t) where the extraction thickness is 10 feet, and from 8.4 to 11.2 feet where the extraction thickness is 14 feet.

Overburden depth above the B-seam longwall centers ranges from approximately 750 to 1,300 feet. With a longwall panel width of 950 feet, maximum subsidence (vertical displacement  $S_m = a \cdot t$ ) is predicted as follows (Table 3) for the Apache Rocks West mining area of panels B12 to B13A:

- *Panels B12 to B13A:* These panels range in width from subcritical to supercritical (width-to depth ratio ( $W/d$ ) ranges from 0.73 to 1.27).
  1. Maximum vertical displacement above the chain pillars ( $S_{cp}$ ) is expected to range from 1.2 to 4.8 feet (0.1 to 0.3t) where the extraction thickness is 12 feet.
  2. Maximum vertical displacement above the mined longwall panels (subsidence,  $S_m = a \cdot t$ ) is projected to range from 7.2 to 9.6 feet (0.6 to 0.8t) where the extraction thickness is 12 feet.

The E-seam panels E10 to E12 and B-seam panels B12 to B13-A occur on top of one another, but are not stacked based on the current panel layout (Figure 1). However, to be conservative, the maximum subsidence (vertical displacement  $S_m = a \cdot t$ ) of the two seams is assumed to be additive.

3. Maximum vertical displacement above the chain pillars ( $S_{cp}$ ) due to both E-seam and B-seam mining cannot be estimated, as the chain pillars for the E-seam and B-seam are not located on top of one another.
4. Maximum vertical displacement above the mined longwall panels (subsidence,  $S_m = a \cdot t$ ) for the B-seam and E-seam mining is projected to range from 13.2 to 17.6 feet (0.6 to 0.8t) where the E-seam extraction thickness is 10 feet, and from 15.6 to 20.8 feet (0.6 to 0.8t) where the E-seam extraction thickness is 14 feet. This estimate is only for the areas over panels E10 to E-12 and B12 to B13-A. Due to the offset

alignment of the E-seam panels from the B-seam panels, the maximum subsidence over E-seam panel E12 will have very little influence from the B-seam mining in panel B13-A.

Sunset Trail Mining Area: Overburden depth above the centers of the projected E-seam longwall panels ranges from approximately 350 to 1,250 feet. With a projected longwall panel width of 1,080 feet, and assuming that the chain pillars (gate road pillars) are similar to those in longwall panel B17 of the Apache Rocks mining area, maximum subsidence (vertical displacement  $S_m = a \cdot t$ ) is predicted as follows (Table 4) for panels SS1 through SS4:

- *Panels SS1 to SS4:* These panels range from subcritical to supercritical (width-to-depth ratio ( $W/d$ ) ranges from 0.86 to 3.09).
  1. Maximum vertical displacement above the chain pillars ( $S_{cp}$ ) is expected to range from 0.9 to 2.7 feet (0.1 to 0.3t) where the extraction thickness is 9 feet, and 1.4 to 4.2 feet where the extraction thickness is 14 feet.
  2. Maximum vertical displacement (subsidence,  $S_m = a \cdot t$ ) is projected to range from 5.4 to 7.2 feet (0.6 to 0.8t) where the extraction thickness is 9 feet, and 8.4 to 11.2 feet, where the extraction thickness is 14 feet.

#### 5.3.1.2 Maximum Tilt

Maximum tilt ( $M_m$ ) was calculated from differential vertical displacements at the West Elk Mine monitoring network in terms of the ratio of maximum vertical displacement to overburden depth ( $S_m/d$  in dimensionless units L/L) (Table 1 and Figure 5). Tilt values at West Elk Mine range from 1.4 to 2.1 percent. Maximum calculated tilt ranges from about two to three times  $S_m/d$  ( $2$  to  $3 \cdot (S_m/d)$ ) at West Elk Mine. Maximum tilt in the Southern Panels, Apache Rocks West, and Sunset Trail mining areas is projected to range from 2.2 to 2.3  $S_m/d$ . Maximum tilt in four different mining areas studied by Dunrud in the Western United States ranges from 2.5 to  $5 \cdot (S_m/d)$ .

#### Southern Panels Mining Area:

As stated earlier in this report, tilt above the nine E-seam longwall panels (panels E1 to E9 and E14) are projected to range between 2.2 and 2.3  $S_m/d$  for coal extraction thickness ranging between 9 and 14 feet. These values are based on subsidence measurements at West Elk Mine (Table 1, Figure 5). The overburden depth above the longwall panel centers ranges from 400 to 1,425 feet (Table 2).

- *Panels E1 to E9 and E14:* Maximum tilt in these panels is projected to range from 0.008 to 0.045 (0.8 to 4.5 percent) where 9 feet of coal is extracted, and from 0.013 to 0.070 (1.3 to 7.0 percent) where 14 feet of coal is mined (Table 2).

Similarly, tilt above the longwall panels (panels B26 to B29) are projected to range between 2.2 and 2.3  $S_m/d$  for coal extraction thickness ranging between 9 and 14 feet. These values are based on subsidence measurements at West Elk Mine (Table 1, Figure 5). The overburden depth above the longwall panel centers ranges from 600 to 1,500 feet (Table 2).

- *Panels B26 to B29:* Maximum tilt in this panel is predicted to range from 0.008 to 0.028 (0.8 and 2.8 percent) where 9 feet of coal is mined, and from 0.012 to 0.043 (1.2 to 4.3 percent) where 14 feet of coal is produced.

The E-seam panels E1 to E5 and B-seam panels B26 to B29 occur on top of one another, but are not stacked based on the current panel layout. However, to be conservative, the maximum tilt ( $M_m$ ) of the two seams is assumed to be additive. The maximum tilt due to two-seam mining is only expected to increase by roughly 20 percent over the maximum for the individual seams.

- Maximum tilt ( $M_m$ ) for the B-seam and E-seam mining is projected to range from 0.010 to 0.054 (1.0 and 5.4 percent) where 9 feet of coal is mined, and from 0.016 to 0.084 (1.6 to 8.4 percent) where 14 feet of coal is produced. This estimate is only for the areas over panels E1 to E5 and B26 to B29.

Apache Rocks West Mining Area:

Tilt above the longwall panels (panels E10 to E12) is projected to range between 2.2 and 2.3  $S_m/d$  for coal extraction thickness ranging between 10 and 14 feet. These values are based on subsidence measurements at West Elk Mine (Table 1, Figure 5). The overburden depth above the longwall panel centers ranges from generally 400 to 1,100 feet (Table 3).

- *Panels E10 to E12:* Maximum tilt in these panels is projected to range from 0.012 to 0.046 (1.2 to 4.6 percent) where 10 feet of coal is extracted, and from 0.017 to 0.064 (1.7 to 6.4 percent) where 14 feet of coal is mined.

Similarly, tilt above the longwall panels (panels B12 to B13-A) are projected to range between 2.2 and 2.3  $S_m/d$  for coal extraction thickness 12 feet. These values are based on subsidence measurements at West Elk Mine (Table 1, Figure 5). The overburden depth above the longwall panel centers ranges from 600 to 1,525 feet (Table 3).

- *Panels B12 to B13-A:* Maximum tilt in these panels is predicted to range from 0.012 to 0.029 (1.2 and 2.9 percent), where 12 feet of coal is mined.

The E-seam panels E10 to E12 and B-seam panels B12 to B13-A occur on top of one another, but are not stacked based on the current panel layout. The maximum tilt ( $M_m$ ) of the two seams is projected to be 20 percent more than the maximum tilt associated with single-seam mining.

- Maximum tilt ( $M_m$ ) for the B-seam and E-seam mining is projected to range from 0.014 to 0.055 (1.4 and 5.5 percent) where 10 feet of E-seam coal is mined, and from 0.020 to 0.077 (2.0 to 7.7 percent) where 14 feet of E-seam coal is produced. This estimate is only for the areas over panels E10 to E12 and B12 to B13A.

Sunset Trail Mining Area: Maximum tilt above the four longwall panels (panels SS1 to SS4) is projected to range from 0.0094 to 0.0473 (0.9 to 4.7 percent) where approximately 9 feet of coal is extracted, and 0.0147 to 0.0736 (1.5 to 7.4 percent) where extraction thickness is approximately 14 feet.

### 5.3.1.3 Maximum Horizontal Strain

Maximum positive horizontal strain ( $E_m$ ) measured at the West Elk Mine monitoring network ranges between 1.1 and 1.4 times ( $S_m/d$ ) (or 0.0058 and 0.0102—that is 0.58 and 1.0 percent); maximum negative strain between -0.20 and -4.0 times ( $S_m/d$ ) (or 0.0009 and 0.0307—0.09 to 3.0 percent) (Table 1). The range of horizontal tensile strain in four different mine areas of the Western United States studied by Dunrud is 0.45 to 3 ( $S_m/d$ ). The curves projected for tensile and compressive strain in the Southern Panels mining area, based on the West Elk Mine monitoring network and the National Coal Board of the United Kingdom, are shown in Figure 5.

Maximum tensile and compressive strain is significantly greater above large barrier pillars and rigid chain pillars and mine boundaries than it is above longwall mining faces. This is because tensile strains caused by mining the two adjacent panels are additive above the common rigid chain pillars or unyielding mine panel boundary pillars. Cracks tend to be wider and deeper above barrier pillars or the interface of mined and unmined coal at the limits of mining (e.g., mineable coal or lease boundary) than chain pillars because of their greater rigidity (for example, the large tension crack on the north side of Lone Pine Gulch).

The tensile strains obtained from the curves in Figure 5 are believed to be conservative for the Southern Panels mining area. Maximum horizontal tensile strains, measured Dunrud in bedrock during annual observations in the Apache Rocks West area (in hard brittle sandstone, where the only strain is revealed by cracks), were 0.0031 to 0.0062 (0.31 to 0.62 percent). These values are about 35 to 45 percent less than those shown in Table 1. The tensile strain is considered to be close to a maximum value for those observed by Dunrud in the Apache Rocks West mining area because 1) the features are located above the area of influence of a large solid coal pillar, and 2) no greater strain was observed in the Apache Rocks West mining area.

#### Southern Panels Mining Area:

Maximum tensile and compressive horizontal strains are calculated, using the values obtained from the area of the West Elk Mine, and as projected in Figure 5 (Table 2). These values are believed to be conservative, based on Dunrud's annual observations in the Apache Rocks West mining area.

- *Panels E1 to E9 and E14:* For these panels, projected horizontal tensile strain ranges from 0.005 to 0.027 (0.5 to 2.7 percent) where the planned coal extraction thickness is 9 feet, and from 0.007 to 0.042 (0.7 to 4.2 percent) where the extraction thickness equals 14 feet.

Horizontal compressive strain ranges from -0.005 to -0.029 (-0.5 to -2.9 percent) where the extraction thickness equals 9 feet, and -0.007 to -0.045 (-0.7 to -4.5 percent) where it equals 14 feet (Table 2).

- *Panels B26 to B29:* For these panels, projected horizontal tensile strain ranges from 0.004 to 0.017 (0.4 to 1.7 percent) where the planned coal extraction thickness is 9 feet, and from 0.007 to 0.026 (0.7 to 2.6 percent) where the extraction thickness equals 14 feet.



Horizontal compressive strain ranges from -0.004 to -0.018 (-0.4 to -1.8 percent) where the extraction thickness equals 9 feet, and -0.007 to -0.028 (-0.7 to -2.8 percent) where it equals 14 feet (Table 2).

The E-seam panels E1 to E5 and B-seam panels B26 to B29 occur on top of one another, but are not stacked based on the current panel layout. However, to be conservative, the strain of the two seams is assumed to be additive.

- For E-seam and B-seam panels, projected horizontal tensile strain ranges from 0.009 to 0.044 (0.9 to 4.4 percent) where the planned coal extraction thickness is 9 feet, and from 0.014 to 0.069 (1.4 to 6.9 percent) where the extraction thickness equals 14 feet.

Horizontal compressive strain ranges from -0.009 to -0.047 (-0.9 to -4.7 percent) where the extraction thickness equals 9 feet, and -0.014 to -0.073 (-1.4 to -7.3 percent) where it equals 14 feet (Table 2).

Apache Rocks West Mining Area:

Maximum tensile and compressive horizontal strains are calculated, using the values obtained from the area of the West Elk Mine, and as projected in Figure 5 (Table 3). These values are believed to be conservative, based on Dunrud's annual observations in the Apache Rocks West mining area.

- *Panels E10 to E12:* For these panels, projected horizontal tensile strain ranges from 0.007 to 0.028 (0.7 to 2.8 percent) where the planned coal extraction thickness is 10 feet, and from 0.009 to 0.039 (0.9 to 3.9 percent) where the extraction thickness equals 14 feet.

Horizontal compressive strain ranges from -0.007 to -0.030 (-0.7 to -3.0 percent) where the extraction thickness equals 10 feet, and -0.009 to -0.042 (-0.9 to -4.2 percent) where it equals 14 feet (Table 3).

- *Panels B12 to B13-A:* For these panels, projected horizontal tensile strain ranges from 0.007 to 0.018 (0.7 to 1.8 percent) where the planned coal extraction thickness is 12 feet.

Horizontal compressive strain ranges from -0.007 to -0.019 (-0.7 to -1.9 percent) where the extraction thickness equals 12 feet.

The E-seam panels E10 to E12 and B-seam panels B12 to 13A occur on top of one another, but are not stacked based on the current panel layout. However, to be conservative, the strain of the two seams is assumed to be additive.

- For E-seam and B-seam panels, projected horizontal tensile strain ranges from 0.013 to 0.046 (1.3 to 4.6 percent) where the planned coal extraction thickness is 10 feet, and from 0.016 to 0.057 (1.6 to 5.7 percent) where the extraction thickness equals 14 feet.

Horizontal compressive strain ranges from -0.013 to -0.049 (-1.3 to -4.9 percent) where the extraction thickness equals 10 feet, and -0.016 to -0.061 (-1.6 to -6.1 percent) where it equals 14 feet (Table 3).

Sunset Trail Mining Area: Maximum tensile and compressive horizontal strains are calculated in the conceptual model, using the values obtained from the West Elk Mine area, and as projected in Table 4. These values are believed to be conservative, based on Dunrud's annual observations in the Apache Rocks mining area.

- Panels SS1 to SS4: For the four panels that extend into the Sunset Trail mining area, the projected horizontal tensile strain ranges from 0.005 to 0.029 (0.5 to 2.9 percent) where the planned coal extraction thickness is 9 feet, and 0.008 to 0.045 (0.8 to 4.5 percent) where the extraction thickness is 14 feet.

Horizontal compressive strain ranges from -0.005 to -0.031 (-0.5 to -3.1 percent) where the extraction thickness equals 9 feet (Table 4), and -0.008 to -0.048 (-0.8 to -4.8 percent) where the extraction thickness is 14 feet.

### 5.3.2 Maximum Projected Depths of Surface Cracks

Curvature, or differential tilt (curvature is the second derivative of vertical displacement with respect to horizontal distance) of subsided rock layers causes horizontal strain. Comparison of calculated curvature values and horizontal tensile strain derived from horizontal displacement measurements, therefore, provides a means of calculating the depth of the neutral surface, and hence the maximum depth of tension cracks from the surface. The neutral surface is the boundary between tensile and compressive strain

In terrains with slopes less than about 30 percent, the depth of the neutral surface can be estimated by dividing the maximum horizontal strain values by those of maximum curvature at a given location. The calculated depth of the tension zone to the neutral surface—the boundary between tension above and compression below—ranges from 50 to 100 feet in the subsidence monitoring network at West Elk Mine. Crack depth may be much less than this projected 50 to 100-foot range of maximum values because most of the monitoring network was located on slopes exceeding 30 percent. An unpublished study for the U. S. Bureau of Mines (Engineers International) indicated that surface crack depth rarely is greater than 50 feet. Cracks will also be less extensive or terminate where shale and claystone layers occur. Based on annual field subsidence observations, maximum crack depth in bedrock in the Southern Panels, Apache Rocks West, and Sunset Trail mining areas is estimated to be 1) 5 to 15 feet in terrain sloping less than, or equal to, 30 percent, 2) 10 to 35 feet in terrain sloping more than 30 percent, and 3) 40 to 50 feet in thick, brittle sandstones in ridges (Tables 2 and 3).

Crack depth will likely be at a maximum value above massive coal barriers. The crack depth is projected to be less (probably 10 to 20 percent less) above the panel chain pillars, where even the rigid pillars are predicted to yield 10 to 30 percent of the coal extraction thickness (Tables 2 and 3).

Cracks that occur above the mined longwall panel area also tend to close, once longwall mining faces move out of the surface area of influence (DeGraff and Romesburg 1981). Any local bed separations during active subsidence between rocks of different strengths (Figure 2) will likely close once equilibrium conditions occur. However, any cracks present above rigid chain pillars, barrier pillars, or the outer limit of mined/unmined coal may remain open where permanent tensile stresses remain after mining is completed due to the convex curvature of the subsidence profile.

During the past ten years of annual observations in the area of the West Elk Mine area by WWE, no cracks were observed above mined-out longwall panels in colluvium more than an estimated ten feet thick. No cracks have been observed in alluvium above mined-out longwall panels. No cracks were observed in the alluvium and colluvium of Sylvester Gulch and Deep Creek (estimated thickness range is 25 to 150 feet) during periodic field observations in the Apache Rocks and Box Canyon mining areas. The near-surface alluvial material consisted of primarily sand, silt, clay, and soil in the two areas mentioned, and was located above rigid pillars and panel boundaries where the overburden depth ranges from 800 to 1,050 feet. Longwall mining has already occurred in the E-seam under Dry Fork, where overburden thickness reaches a minimum of less than 400 feet. No cracks were observed in the alluvium of Dry Fork following longwall mining; therefore, no significant cracking in alluvial and colluvial deposits is anticipated with proposed mining in the Southern Panels mining area. The Sunset Trail mining area will include South Prong, where conditions are expected to mirror mining under Dry Fork, where alluvial and colluvial deposits are present. Reaches of South Prong underlain by bedrock will be more prone to surface cracking, with projected depths of 5 to 15 feet.

The probable reason for the lack of cracking in alluvial and colluvial deposits is that the fine sand-to clay-sized material and overlying soil can yield without cracking or bulging as it deforms as a discrete unit or units during the subsidence process. The alluvium in the Southern Panels and Sunset Trail mining areas is estimated to vary in thickness from about 25 feet to 75 feet. This same reasoning also applies to the colluvium in the area. Although subsidence cracks were locally observed in colluvium less than a foot to a few feet thick, no cracks were observed in colluvium more than about 10 feet thick.

#### **5.4 Angle of Draw**

The draw, or limit, angle ( $\phi$ , from a vertical reference) in the Somerset area ranges from about 8 to 21 degrees. The angle of draw measured for F-seam room-and-pillar mining at West Elk Mine, which has overburden rock lithology similar to the-E-seam, ranged from 11.3 to 16.1 degrees and averaged 14.4 degrees. The angle of draw for B-seam longwall mining at West Elk ranges from about 15 to 17 degrees after accounting for F-seam mining influence (Table 1). MCC collected survey data from the subsidence monuments following mining of E-seam longwall panel E1. WWE's analysis of that data indicates that the mean angle of draw is approximately 16°, with a range of 14° to 19° predicted for the Southern Panels (Table 2) and Apache Rocks West (Table 3) mining areas. For the Sunset Trail mining area, the angle of draw is projected to range from 14° to 19° (Table 4).

## 5.5 Break Angle

The break angle, the angle ( $B$ , from a vertical reference) of a straight line projected from the zone of maximum horizontal tensile strain at the ground surface to the boundary of the mine workings, is more important than the draw angle for hydrologic analyses (Figure 3). The break angle provides a means of determining zones, in relation to underground mine workings, where near-surface water most likely may be impacted. The break angle generally averages 10 degrees less than the corresponding draw angle, according to Peng and Geng (1982).

The break angle ranges from -9 to 3 degrees in the West Elk Mine subsidence monitoring network area (Table 1). Topography appears to control the location of the zone of maximum tensile strain and consequently the break angle. For example, the break angle is 3 degrees where tilt direction (caused by subsidence) is opposite to the direction to the slope of the ground surface (42 percent slope), but is -9 degrees where the tilt direction is in the same direction as the slope of the ground surface (32 percent slope) (Table 1).

Tensile strain caused by subsidence commonly reaches a maximum value in linear zones above mining panels. The location of these zones can be determined by the break angle (the angle of the break line from panel boundaries to the zone of high tensile strain. At panel boundaries with solid coal, subsidence data from the West Elk Mine monitoring network shows that the break angle for subcritical mining panels ranges from -9 to 3 degrees with an average expected value of about 0 degrees.

Information from the West Elk Mine subsidence monitoring network also indicates that the zone of increased horizontal tensile strain ranges from 100 to 150 feet wide above mine boundaries and from 100 to 250 feet wide above the chain pillars. This zone, which is also predicted for the Southern Panels, Apache Rocks West, and Sunset Trail mining areas, is located approximately above the edges of the panels or slightly outside the panel boundaries and above the center of the chain pillars, unless a down-slope component of movement occurs on steep slopes in addition to the differential tilt component. Cracks tend to be more common and more permanent in zones above mine boundaries, barrier pillars, and unyielding chain pillars. Any surface or near-surface water that might be present in this zone has a higher probability of being impacted than that occurring in any other areas above the mining panels.

## 5.6 Angle of Major Influence

The angle of major influence,  $\beta$ , (also called angle of influence of the point of evaluation) is defined by Peng (1992, p. 11) “. . . as the angle between the horizontal and the line connecting the inflection point and the edge of the radius of major influence.” The radius of major influence ( $r$ ) is therefore the horizontal distance from the vertical projection of the inflection point to the point of maximum subsidence and the limit of subsidence (Figure 3). The angle of major influence is used for computer modeling by the influence function method. In the B-seam mining at West Elk Mine, the angle of major influence ranges (from a horizontal reference) from about 70 to 80 degrees.

The angle of major influence may also be referenced to the vertical, as has been done for the break angle and angle of draw. The angle of major influence (from a vertical reference) is roughly equal

to the angle of draw (Figure 3), and is therefore also predicted to range from 10 to 20 degrees for both B-seam and E-seam panels.

### **5.7 Relation between Dynamic and Final Subsidence Deformations**

Maximum dynamic tilt (change of slope) and horizontal tensile and compressive strain are reportedly less above longwall mining panels than are the final tilt and strain values at panel boundaries. Dynamic tilt and strain decrease, relative to final tilt and strain, as the rate of face advance increases.

Dynamic tilt and strain reportedly decrease with increasing speed of longwall coal extraction (Peng 1992, p. 20-21). Based on observations in a West Virginia coal mine:

1. Maximum dynamic tilt decreased by an average of 42 percent (from 0.0024 to 0.0014) as the mining face rate of movement increased from 10 to 40 feet per day; dynamic tilt therefore decreased by 14 percent as the face rate of movement increased by 30 feet per day.
2. Maximum dynamic tensile strain decreased by an average of 22.5 percent (from 0.0031 to 0.0024) as the mining face velocity increased from 10 to 40 feet per day; dynamic horizontal tensile strain decreased by 7.5 percent as the face increased by 30 feet per day.
3. Maximum dynamic compressive strain decreased by an average of 48 percent (0.0062 to 0.0032) as the face velocity increased from 10 to 40 feet per day; dynamic horizontal compressive strain decreased by 16 percent as the face increased by 30 feet per day.

### **5.8 Critical Extraction Width of Mining Panels**

Critical extraction width ( $W_{cr}$ ) is the width of mining panels necessary for maximum subsidence to occur at a given overburden depth ( $d$ ). Values for  $W_{cr}/d$  typically range from about 1.0 to 1.4, with an average of about 1.2. Based on the subsidence development data for the 5th NW longwall panel, the critical extraction width may be closer to the average value of 1.2 than 1.4 in the Southern Panels, Apache Rocks West, and Sunset Trail mining areas (Figure 4).

### **5.9 Results of Computer Modeling**

A computer software package was used to model the results of subsidence measurements at West Elk Mine and to project subsidence in the Southern Panels, Apache Rocks West, and Sunset Trail mining areas. The package used is entitled: "Surface Deformation Prediction System (SDPS)", Version 6.2G developed by Department of Mining Engineering, University of Kentucky; Department of Mining and Minerals Engineering, Virginia Polytechnic Institute and State University. This program performed an influence function analysis and best fit of West Elk Mine subsidence data. The fit between the data points and the influence function output from the model is shown in Figure 6. Considering that there was some F-seam influence on the B-seam subsidence data, the actual subsidence measurements and subsidence profiles predicted by the influence function model compare favorably.

WWE further calibrated the computer model using subsidence monitoring data collected over E-seam panels E1 to E3. While the model over predicted the subsidence over panel E1, the previous calibration accurately predicted the subsidence along the Dry Fork survey points. Therefore, WWE elected to use the more conservative parameters, recognizing the model results may over-predict subsidence.

Once the computer program was calibrated to the West Elk Mine subsidence data, subsidence was then projected into Southern Panels, Apache Rocks West, and Sunset Trail mining areas using representative coal extraction thicknesses and overburden depths for the respective panels in order to obtain an independent check on the subsidence projections based on the conceptual model.

Comparison of the Dunrud's conceptual model calculations and the influence function of the SDPS computer model (which were done by WWE in Figures 7, 7A, 8, and 9) show the following:

1. Maximum vertical displacement (subsidence) above the chain pillars in the transverse profile (Figures 7 and 7A) is close to the maximum values predicted in the conceptual model calculations. Maximum vertical displacement above the longwall panel centers, however, is about equal to the median values projected in the conceptual model calculations.
2. The ranges calculated for vertical displacement in the conceptual model are conservative. The ranges account for rapidly changing overburden thicknesses in the local rugged terrain of the Southern Panels, Apache Rocks West, and Sunset Trail mining areas and for changing lithology—such as lenticular sandstones, coal seams, and shales—in the overburden rocks.

## **6.0 RATE AND DURATION OF SUBSIDENCE**

A point on the surface begins to be affected when the longwall mining face is within  $0.1d$  to  $0.6d$  ( $d$  = overburden depth) of the point and is near maximum downward velocity. Subsidence is 50 percent complete when the face is  $0.2d$  to  $0.5d$  beyond the point, and is more than 90 percent complete when the face is  $1.0d$  to  $1.4d$  (average about  $1.2d$ ) beyond the point if longwall mining is done. Data obtained above the 5th NW longwall panel at the West Elk Mine plot between the National Coal Board (NCB) and Somerset curves (Figure 11). The data also show that subsidence is more than 95 percent complete when the longwall face has moved  $1.0d$  beyond the points of measurement. Critical extraction width, therefore, is approximately  $1.0d$  for the B-seam panels at West Elk Mine, and is projected to range from  $1.0d$  to  $1.2d$  for the Southern Panels, Apache Rocks West, and Sunset Trail mining areas.

Subsidence monitoring data collected over E-seam longwall panel E1 provides additional information on the rate and duration of subsidence at West Elk Mine. Survey measurements taken 11 days after the longwall passed beneath the point showed that total subsidence was 93 percent complete. The location of the longwall face was  $1.5d$  beyond the survey point at the time of measurement.

Rate and duration of subsidence above longwall mining panels, therefore, are a function of mining rate. The faster and more uniformly the longwall face moves, the less time any surface cracks present will be open to potentially impact surface or ground water. Therefore, rapid, uniform mining beneath streams and other sensitive features causes minimum mining impact.

The duration of subsidence above room-and-pillar mines is less predictable, however, because not all pillars are removed. In Figure 11, subsidence at a given point ( $p$ ) was only about 60 percent complete after room-and-pillar mining was completed within the area of influence of the point.

## **7.0 EFFECTS OF TOPOGRAPHY AND STRUCTURE ON SUBSIDENCE PROCESSES**

In contrast to subsidence of rock units as fixed-end, laterally constrained, multiple plates, subsidence in steep topography may occur as non-fixed end, laterally unconstrained multiple plates (rock units). This lack of lateral confinement may cause reversals of horizontal displacement and excessive tensile strain may occur on steep slopes. Peng and Hsuing (1986) found that horizontal displacement is affected by slopes greater than 20 percent. Displacements on steep slopes and cliffs can cause cracks to open more along faults, fractures, and joints than would occur in subdued topography where the rock units are laterally constrained. Therefore, steep slopes and cliffs, which commonly are susceptible to rockfalls and landslides anyway, may become less stable when undermined.

The topography is less rugged in the Southern Panels and Sunset Trail mining areas than in the Box Canyon mining area, while the Apache Rocks West mining area is comparable. However, there are steep slopes and local cliffs and ledges. Therefore, these steeper slopes and cliffs may become less stable when they are undermined.

### **7.1 Effects of Topography on Subsidence Cracks**

Cracks commonly are wider, deeper, and may remain open longer above rigid chain pillars or mine boundaries on steep slopes where there is little or no lateral constraint. In addition, the direction of mining relative to slope direction may control crack width, depth, and abundance. For example, tension cracks were observed to be wider, deeper, and more abundant on steep canyon slopes that faced in the direction of mining than they were on slopes facing in directions opposite the mining direction (Dunrud and Osterwald 1980, p. 26-29; Gentry and Abel 1978, p. 203-204).

Cracks are projected to be the widest and deepest on the steep slopes, cliffs, and ridges adjacent to and on either side of Minnesota Creek and its tributaries, as well as Lick Creek, South Prong, and Deep Creek. Maximum crack depth on these steep slopes and cliffs is estimated to locally be from 15 to as much as 35 feet deep. Due to the lack of lateral constraint, these cracks may remain open until they are filled by processes such as sheet wash and sedimentation.

### **7.2 Effects of Rugged Topography on Subsidence and Mine Stresses**

The subsidence factor ( $\alpha$ ) reportedly can vary significantly in draws and on ridges in rugged topography. Gentry and Abel (1978, p. 203-204) report that vertical displacement was 25 to 30 percent greater on a ridge than it was in an adjacent draw in the York Canyon (Raton, New Mexico) longwall mining area (Figure 4). Based on this information, the subsidence factor is projected to be closer to 0.6 in deep draws and closer to 0.8 on isolated points and ridges in the Southern Panels, Apache Rocks West, and Sunset Trail mining areas. No significant similar influence is expected in these mining areas because there are few, if any, isolated ridges.

Based on observations by Dunrud in the Somerset Mine in the mid-1970s, stresses tended to be significantly higher beneath isolated ridges than they were beneath more uniform overburden of similar thickness. For a similar mine geometry, roof falls, bumps (rock bursts), and floor heaving were noticeably greater beneath the ridges than they were beneath more uniform overburden of



similar thickness, because there is little or no lateral constraint to distribute the weight of the isolated load of the ridge.

## **8.0 FRACTURE-CONTROLLED DRAINAGES**

Based on mapping in the Southern Panels mining area, Dunrud believes that there is reasonably good, but certainly not conclusive, evidence that some drainages are controlled by fractures and/or joints. The Dry Fork of Minnesota Creek and some of its tributaries exhibit linear trends on satellite images and on high-altitude photographs that indicate, or at least suggest, fracture control (Dunrud 1976, p. 14-15). These fractures may have been caused in part by stresses generated by the West Elk Mountain intrusive bodies—particularly Mt. Gunnison.

The conservative approach may be to assume that the drainage system is fracture controlled. However, even if fractures control the present drainage system, they may not extend downward as continuous joints of fractures to the E-seam located several hundreds of feet below. Even if the fractures were present in the more brittle sandstone units, it would be very unlikely that these fractures would occur in the softer siltstone and shale units. Even under the conservative approach that the drainages in the Southern Panels, Apache Rocks West, and Sunset Trail mining areas are fracture controlled, it is extremely unlikely that they extend downward to the E-seam through multiple shale, claystone, and siltstone units. Using this conservative evaluation, it is now important to evaluate the potential impact that subsidence may have on any pre-mining fractures.

Evaluation of subsidence due to downwarping of laterally constrained strata shows, as stated previously, that rock strata with different deformation and strength characteristics deform as discrete units. For example, strata of shale and siltstone behave as units discrete from sandstone. Above the fractured zone (Section 4.2) and within the continuous deformation zone (Section 4.3) these units undergo continuous flexure (Figure 2, enlargement 2). Above the neutral surfaces, in zones of convex-upward curvature, the material is in tension and below them, and the material is in compression.

Consequently, stresses change across neutral surfaces from tension to compression across each successive rock unit that deforms as a plate. Fractures already present would thus tend to open more in the zones of tension, but would close more in the zones of compression, which would close these fractures more than they were prior to mining and subsidence.

After longwall mining is completed in the area and static conditions are attained, the zones of tension and compression commonly cease, and any fractures present will likely resume the pre-mining condition. Therefore, the impacts on surface flow in the drainages of the Southern Panels, Apache Rocks West, and Sunset Trail mining areas are likely to be minimal or non-existent under even the most conservative assumptions.

## **9.0 WATER AND METHANE**

Observations of the north and west flanks of Mt. Gunnison during aerial geologic mapping and an October 1996 field trip revealed numerous talus and rock glacier deposits that occur in the valleys and lower part of this intrusive body. Snowmelt and rain can easily infiltrate these deposits, which may eventually enter any permeable rocks, faults, fractures, and joints near the mountain. Coal beds and rocks in the deformed zone around Mt. Gunnison may also contain increased concentrations of methane where the coal is deformed and perhaps metamorphosed to a higher rank by the intrusive body. Greater quantities of water and methane may therefore be expected as coal is mined closer to Mt. Gunnison.

### **9.1 Potential Impact of Water on Subsidence in Wet Mining Areas**

As discussed in Section 3.0, the moisture content of the caved and downwarped rocks controls the amount of subsidence that can be expected. In the Southern Panels, Apache Rocks West, and Sunset Trail mining areas where water might be encountered in an area equal to, or greater than, the width of the proposed longwall panels, maximum vertical displacement may be expected to approach 0.8t.

## 10.0 POTENTIAL IMPACTS OF SUBSIDENCE AND MINE-INDUCED SEISMIC ACTIVITY ON LANDSLIDES AND ROCKFALLS

### 10.1 Landslides

The landslides listed below are all naturally occurring features, which become less stable, or become unstable and slide, during periods of increased precipitation. A review of aerial photographs of the Apache Rocks and South of Divide mining areas, which were taken in 1963 and 2004, show that the slides listed below appeared to be more stable in 1963 than they are now. Mr. C. Richard Dunrud (retired U.S. Geological Survey coal mine subsidence expert and author of USGS Map C-115) observed that many of the existing landslides during periods of high precipitation were less stable, or became unstable and moved in the mid-1980s and mid-1990s. Landslides were identified in the Dry Fork mining area as part of the Final Environmental Impact Statement (2005). Map 1 is a composite showing the landslides in the Southern Panels mining area.

The landslides in the southeast side of West Flatiron and on the west side of Deep Creek in the Apache Rocks mining area showed no visual effects when longwall mining occurred beneath the areas. It therefore seems apparent that wet seasons affect landslides more than does longwall mining. During very wet periods, however, landslides that are already unstable may locally be triggered by mine subsidence.

A total of twelve landslides, landslide areas, or landslide and rockfall areas, have been mapped in the Apache Rocks West and Southern Panels mining areas during field mapping with the U.S. Geological Survey (USGS) in the 1980s and also during the annual subsidence observations in these areas.

1. Apache Rocks West mining area:

- a. Landslide located just north of Minnesota Reservoir in SW $\frac{1}{4}$  of Section 29. Mining of the B-seam longwall panels B12, B13, and B13-A did not have any observable effect on the landslide.
- b. Landslide area located above mined longwall panels E14 and E15 in NW $\frac{1}{4}$  of Section 26. These landslides appeared to be unaffected by longwall mining beneath them.
- c. Landslide area located on the west side of Deep Creek, located above the southeastern part of mined B-seam longwall panel 17 in the NW $\frac{1}{4}$  of Section 35. This landslide also appeared to be unaffected by mining below when observed in July 2003.

2. Southern Panels mining area (Map 1):

- a. An extensive landslide is located south of Minnesota Reservoir north of the projected E-seam longwall panel E9, in the N $\frac{1}{2}$  of Section 32, Township 13 South, Range 90 West (Dunrud 1989). Overburden depth to the E-seam ranges from 500 to 600 feet. The average slope of the slide is roughly 20 percent. The landslide contains more cracks and scarps in the upper part and more depressions and bulges in the lower part

than were present in the early 1960s (based on image data from July 1963 aerial photographs).

- Based on a stereographic review of July 2004 vertical aerial photographs, renewed activity occurred locally in western part of the landslide areas north and south of Dry Fork during wet periods in the 1980s (1984 to 1987) and the mid-1990s (1994-1996). The Dry Fork road was taken out one half-mile west of the Minnesota Reservoir dam by this renewed movement in 1987 (Map 1).
- b. Landslides were identified on the Dry Fork mining area in the Final Environmental Impact Statement prepared for the U.S. Department of Agriculture – Forest Service in August 2005. The report identified three active landslide areas in the southeast corner of the area. These are located outside the area of influence from mining in longwall panels E4 and E5. The erosional escarpment at the headwaters of Deep Creek is also outside of the area of influence mining. Two small landslides (slope failures) were identified by a Tetra Tech geologist during a site inspection on September 20, 2007. These are located just above the Deep Creek Ditch.

3. Sunset Trail mining area:

- a. As shown on Map 1, there are several identified landslides within the Lick Creek drainage and others near the mouth of South Prong. Most of the mapped features will be outside the influence of mining, while the remaining few will be monitored throughout mining.

#### *10.1.1 Effects of Subsidence and Mine-induced Seismic Activity on Landslides*

Some of the most important information regarding mine subsidence and mine-induced seismicity was obtained from observations of active landslides on Jumbo Mountain above B-seam longwall panels 8 and 9, which were mined during the mid-1990s. Landslide movement occurred during unusually wet periods before mining, during mining, and after mining and subsidence was complete. The landslides located north and south of Minnesota Reservoir are similar to those on Jumbo Mountain. Both occur in surficial material (rocks, gravel, sand, silt, clay, and soil) and local outcrops of bedrock that have slumped and flowed downhill during periods of increased saturation. Cracks, bulges, and depressions or troughs, and springs were locally observed in both landslide areas.

It is important to note that no earth tremors (seismic activity) were felt by Mr. Dunrud and other field observers in all the annual traverses and observations made above the longwall mining areas in the Jumbo Mountain, Apache Rocks, Box Canyon, Southern Panels, and Sunset Trail mining areas during the past 25 years (1996-2020 inclusive). For example, no tremors were felt during the annual traverse above B-seam longwall panel 13 in 1999, when the mining face was located directly beneath one of the subsidence observation points. This point was located approximately 1,200 feet vertically above the active mining face, and 2,800 feet north of Minnesota Reservoir.

In contrast to room-and-pillar mining, longwall mining is a uniform extraction procedure that basically involves 1) the uniform cutting of a coal face, 2) the caving of the roof behind the moving

coal face, and 3) the recompression of the caved material behind the support system. This system therefore causes only a minimum amount of very low magnitude seismic activity (below the threshold of feeling at the ground surface), particularly where the overburden depth to the coal being mined is less than about 1,500 feet.

Based on field observations during the past 25 years, the major finding is that landslide movement occurs in response to moisture and ground saturation, and is not noticeably affected by subsidence or any mine-related seismic activity caused by longwall mining beneath or near the landslides.

Based on the above-mentioned historical evidence from the annual observations, the landslide areas located north and south of Minnesota Reservoir are not expected to be impacted by mine-induced subsidence and seismic activity when longwall panel E9 is mined.

With regard to the landslide north of Minnesota Reservoir, longwall mining in the B-seam panel B13-A did not have any observable effect on the landslide. The proposed E-seam mining in panel E12 will occur further south and with shallower overburden. As shown in Map 1, the head of the landslide will be located over the southern edge of panel E12, where subsidence is projected to be between 4 and 4.5 feet. As a result, the upper portion will be subject to subsidence with the outcome being a flattening of the slope in the upper reaches of the slide. This flattening of the upper reaches of the slide will reduce the movement potential and likely focus any movement that might occur to just the upper reaches. In addition, the overall slope of the mapped slide is less than in adjacent areas, further suggesting greater stability and a reduced potential for reactivation.

Lastly, Mr. Dunrud has reviewed the conditions associated with the proposed mining activities and the mapped landslide. It is his opinion that while subsidence might cause minor reactivation of the landslide near the upper end, it is unlikely that there will be any movement that would reach or effect Minnesota Reservoir.

## **10.2 Rockfalls**

Rockfalls are the free-falling movement of rocks, which have become detached from cliffs or other steep slopes, and move under the influence of gravity and the underlying ground surface. The detached rocks roll and/or bounce downhill, depending on the slope (configuration of the ground surface). Their movement continues until they are stopped by an obstruction or lose potential energy and stop naturally.

A low to high potential exists for rockfalls in the Southern Panels and Sunset Trail mining areas. Analysis of the terrain in these mining areas reveal slopes that range from 30 to 80 percent along Minnesota Creek, the Dry Fork of Minnesota Creek and its tributaries, and in local areas along the main fork of Lick Creek. Vertical displacement, tilt, and strain produced by mining may locally trigger already unstable rocks to fall during, or shortly after mining.

The areas with steep slopes in the Southern Panels and Sunset Trail mining areas, which have the greater potential for rockfalls, are located either in areas with local access roads, which have only limited travel, or in areas remote from any access roads or other man-made features. Based on a review of aerial photographs and analysis of the USGS 7.5-minute quadrangles, there are areas with slopes ranging from 30 to 80 percent that contain local cliffs and ledges (small cliffs 5 to 10

feet high). The general areas listed below (listed in an east-to-west, north-to-south direction) have a low to high rockfall potential (Map 1):

1. Steep slopes (with an estimated rockfall potential ranging from moderate to high) located north of Dry Fork and west of Minnesota Reservoir. However, no mining is planned in this area, so this rockfall area would not be impacted.
2. Two steep ridges with cliffs and ledges, located above the northern part of longwall panel E9 east of the landslide area described in Section 10.1 (mostly in the SE $\frac{1}{4}$  of Section 32, Township 13 South, Range 90 West). There are no roads or man-made structures in the area.
3. The south end of a steep ridge containing cliffs and ledges located north of Minnesota Reservoir and Dry Fork and north of the confluence of Deer Creek and Dry Fork above the western edge (within the area of mining influence) of longwall panels E1 and E2 (S $\frac{1}{2}$ , Section 29 and the NW $\frac{1}{4}$  of Section 33, Township 13 South, Range 90 West). The Dry Fork road is located 400 to 500 feet south of the nearest area boundary. Following mining in these longwall panels, no additional rockfall was observed during semi-annual field studies.
4. A steep to moderately steep slope containing eight separate rockfall areas, located north and south of Dry Fork and its tributaries. The estimated rockfall potential is low to moderate. The rockfall areas are located above longwall panels E1 to E4 (Sections 33 and 34 and the NE $\frac{1}{2}$  of Section 35, Township 13 South, Range 90 West). Following mining in these longwall panels, no additional rockfall was observed during semi-annual field studies.
5. The area is located in the southwestern part of the South of Divide mining area east of the main fork of Minnesota Creek. While the majority of this area is located outside the influence of mining, the northeastern part of this area, which has an estimated moderate to high rockfall potential, is within the area of mining influence of the western and southern part of longwall panels E8 and E9, respectively (located mostly in the W $\frac{1}{2}$  and S $\frac{1}{2}$ , Section 5, Township 14 South, Range 90 West).
6. This area contains six rockfall areas that have locally steep ridges. The area is located near the headwaters of Deer Creek, Poison Creek, Lick Creek, and a tributary of Dry Fork. The areas, which have an estimated low to moderate rockfall potential, are located above, or partly within, the area of mining influence of longwall panels E5 to E8, and SS1 (located in parts of Sections 3, 4, 9, and 10, Township 14 South, Range 90 West).
7. This area contains three rockfall areas that have an estimated low to high rockfall potential. It is located in the Lick Creek area and above, or partly within, the area of mining influence of longwall panels E14 and SS1 to SS4 (located in parts of Sections 8, 9, and 16, Township 14 South, Range 90 West).
8. This area is located on the east side of the main Deep Creek channel above longwall panel E3. This area is identified as having low to moderate rockfall potential. It is located in an

area too remote for any access roads or manmade features. Following mining in these longwall panels, no additional rockfall was observed during semi-annual field studies.

9. This area is located on the eastern boundary of the Deep Creek watershed. This rockfall area would have been over the eastern ends of panels E3, E4, and E5 if mined to the maximum projected potential extent. However, based on where mining stopped in these panels, the rockfall areas were outside the influence of mining.

Of the areas listed above, most occur near local drill roads or agricultural access roads, which have only local, limited traffic on them. Any rocks that may fall in these areas could be readily removed before local traffic is impacted, should rockfalls occur on these remote roads. Evidence of naturally occurring rockfalls, such as remnant boulders located at the base of steep slopes, or in the run-out zones of these areas, and documentation of these areas prior to mining is recommended.

Based on semi-annual observations in the Apache Rocks, Box Canyon, Southern Panels, and Sunset Trail mining areas, subsidence and any seismic activity caused by longwall mining is not expected to significantly affect rockfall areas with an estimated high to low rockfall potential. Only rockfall areas with an estimated very high rockfall potential were noticeably affected. However, because there are no rockfall areas with an estimated very high rockfall potential in the Southern Panels and Sunset Trail mining areas, the planned longwall panels in these mining areas will most likely not affect rockfall areas.

### **10.3 Importance of Baseline Landslide and Rockfall Data**

The most significant landslide in the Southern Panels mining area, in terms of proximity to man-made structures, is located above the northern part of E-seam longwall panel E9 (Map 1). Although there is a large landslide within the area of mining influence of the southeast corner of E-seam longwall panel E8 (mostly in the NE $\frac{1}{4}$  of Section 8), the landslides located north and south of Minnesota Reservoir are the most important in the mining area. Existing, natural (baseline) conditions are monitored before mining begins in order to document their natural state. The cracks, bulges, and depressions observed in the landslide areas north and south of Minnesota Reservoir are much more extensive and dramatic than those caused by subsidence. The vertical aerial photographs obtained by the West Elk Mine (dated July 2, 2004) provide good baseline images of all the natural, pre-mine features in the Southern Panels mining area.

Observations made by WWE in the area of the West Elk Mine indicate that mining may accelerate the natural landslide process, where there are landslides that have already become unstable. However, annual observations of the surface cracks and depressions in the landslide area on Jumbo Mountain above mined B-seam longwall panels 8 and 9 determined that landslides are very likely only related to natural mass-gravity movements and not related to mining.

Baseline observations and photographs have been gathered in the areas with low to moderate rockfall potential that are listed in Section 10.2 prior to mining activities. Evidence of naturally occurring rockfalls, such as remnant boulders of the base of steep slopes, or in the run-out zones of these areas with a rockfall potential have been documented prior to mining.



## **11.0 EFFECTS OF SUBSIDENCE AND MINE-INDUCED SEISMIC ACTIVITY ON MAN-MADE STRUCTURES AND RENEWABLE RESOURCES**

Man-made structures and renewable resources in the Southern Panels, Apache Rocks West, and Sunset Trail mining areas basically consist of 1) a reservoir (Minnesota Reservoir), 2) stock watering ponds, 3) streams (primarily Dry Fork and the upper part of Lick Creek) and Deep Creek Ditch, 4) roads, and 5) local cabins. Minnesota Reservoir, the ponds, and the Deep Creek Ditch diversion to Dry Fork serve the dual purpose of being both man-made structures and containment structures for the valuable water resources in the area. Based on annual subsidence observations in the Jumbo Mountain, Apache Rocks, Box Canyon, and South of Divide mining areas since 1996, the following information is considered appropriate for the Southern Panels, Apache Rocks West, and Sunset Trail mining areas.

### **11.1 Minnesota Reservoir**

Minnesota Reservoir, which provides storage water primarily for irrigation, is located between two landslides—one beginning at the north shore and the other beginning at the south shore. As explained in Section 10.1.1 (above), landslide movement on Jumbo Mountain occurred during unusually wet periods before mining began, during mining, and after mining and subsidence was complete. The conclusions were that landslide movement occurs in response to ground saturation and is not noticeably affected by subsidence and seismic activity produced by longwall mining beneath, or near, landslide areas.

Both the landslides on Jumbo Mountain and those north and south of Minnesota Reservoir occur in surficial material (loose rock, gravel, sand, silt, clay, and soil) and local bedrock outcrops. Dunrud therefore expects that the mining of longwall panel E9 will not noticeably affect the large landslide south of Minnesota Reservoir.

Mining of the longwall mining panels in the Southern Panels, Apache Rocks West, and Sunset Trail mining areas, as currently planned (Map 1) will not affect Minnesota Reservoir. The reservoir is located outside the area of mining influence of both the B- and E-seam panels, using an extremely conservative 45-degree angle of draw. Monitoring data is presented in the annual Fall Subsidence Reports to verify and demonstrate the accuracy of the predictions.

### **11.2 Stock Watering Ponds and U.S. Forest Service Water Resources**

The stock watering ponds in the Southern Panels mining area are located in debris flows or colluvium derived from the debris flows (Dunrud 1989). Some of these ponds are also classified as U.S. Forest Service water resources. The debris flows consist of a heterogeneous mixture of clay derived from the Wasatch Formation and boulders and gravels derived primarily from the Mount Gunnison intrusive (granodiorites and quartz monzonites). Based on observations made during geologic mapping in the area, these debris flows are even less likely to be affected by longwall mining than the alluvium. The debris flows have a very low permeability and, because the clay matrix is armored by the interstitial gravel and boulders, are resistant to erosion (the Deep Creek Ditch locally flows in this material at steep gradients). Based on the above-mentioned observations, no effects are expected when ponds in the Southern Panels, Apache Rocks West, and

Sunset Trail mining areas are undermined. The clay-rich material that lines these ponds is expected to provide a seal against subsidence effects.

Numerous observations have been made of the stock watering ponds and U.S. Forest Service water resources over both B-seam and E-seam longwall mining. Based on years of field studies, none of these resources has been noticeably affected when longwall mining occurred beneath them. These observations are documented in the annual Subsidence and Geologic Field Observations reports.

### **11.3 Streams and Ditches**

The primary streams in the Southern Panels mining area are Dry Fork of Minnesota Creek, Deep Creek, Poison Creek, and Lick Creek. A primary source of water to the Dry Fork and Minnesota Reservoir comes from the Deep Creek Ditch, wherein the trans-basin water is conveyed through the upper drainage of Deep Creek and transmitted to Dry Fork. The Deep Creek Ditch was constructed in debris flows or colluvium and alluvium derived from the debris flow, as described in Section 11.2, this debris flow material is not expected to be impacted by longwall mining. There is an area of the Deep Creek Ditch that has a hard rock bottom. This area is limited to the lower gradient areas above the first landslide in the Dry Fork mining area (Refer to Map 1). The Deep Creek Ditch is not anticipated to be affected by longwall mining based on the eastern extent of E-seam longwall panel E5 and the projected extent of longwall panel E6.

Longwall mining of the E-seam panels E1 to E5 has occurred under Dry Fork where the overburden depth above the longwall panels drops as low as about 375 feet. No adverse impacts were observed during or subsequent to the longwall panel mining. The proposed B-seam panels B26 to B29 will have 200 to 300 feet of additional overburden, and do not extend as far west as the E-seam panels where the overburden under the Dry Fork channel is at a minimum. In the Apache Rocks West mining area, Horse Gulch enters Minnesota Reservoir from the north and has already had longwall mining occur beneath it in B-seam longwall panels B12 to B13-A with no apparent cracking in the alluvial material. Although E-seam mining had less overburden (down to about 350 feet), the experience of mining beneath Dry Fork with similar overburden indicated that there will not be adverse impacts to the Horse Gulch channel even though the alluvial thickness is less than Dry Fork.

As discussed in Section 5.3.2, no cracks were observed in the alluvium and colluvium of Sylvester Gulch, Deep Creek, and Dry Fork during periodic field observations. The near-surface alluvial material consists of primarily sand, silt, clay, and soil that ranges in estimated thickness from 25 to 75 feet. The alluvium and colluvium in Dry Fork and Lick Creek, which also has an estimated thickness range of 25 to 75 feet, contains more clay than does the Deep Creek alluvium. Therefore, it is even less likely that cracks will occur in colluvium and alluvium in the stream valleys of the Southern Panels mining area despite the shallow overburden.

The Sunset Trail mining area includes South Prong and some of its tributaries. The channels all have steep gradients and are not anticipated to be adversely affected by longwall mining of Panels SS1 to SS4. Exhibit 55B addresses potential impacts to South Prong in more detail.

The probable reason for the lack of cracking in alluvium is that the fine sand-to clay-sized material and overlying soil yields without cracking or bulging as it deforms as a discrete unit, or as discrete units, in the subsidence process. This same reasoning also applies to the colluvium in the area. Although mined longwall panel subsidence cracks were locally observed in colluvium less than one foot to a few feet thick, no cracks were observed in colluvium more than about ten feet thick. No cracks were observed in alluvium above mined longwall panels in the Apache Rocks and Box Canyon mining areas.

### *11.3.1 Potential for Hydraulic Connection between Mine Workings and Surface*

Near the southwest corner of E-seam longwall panel E2, the Dry Fork channel encounters a short reach where the E-seam overburden above the longwall panel block is less than 400 feet, with a minimum of approximately 375 feet. A prudent concern is whether mining induced longwall panel subsidence could establish a hydraulic connection between the Dry Fork stream channel and the mine workings. To address this scenario, the maximum projected height of longwall panel fracturing and the maximum depth of surface cracks were considered. As discussed in Section 5.2, the effective height of longwall panel fracturing in the Southern Panels and Sunset Trail mining areas is estimated to range from 9t to 18t, or a maximum fracture height of 252 feet for a mining height of up to 14 feet. However, Peng (1992) states that the upper one-third of the longwall panel fractured zone has only minor fractures with little potential for water conductivity. Therefore, the height of the fractured zone capable of transmitting water would be two-thirds of the 18t, or 168 feet.

The maximum height of the mined longwall panel caved zone is projected to be 5t, or 70 feet, for the Southern Panels and Sunset Trail mining areas with a projected mining thickness of up to 14 feet. The maximum mined longwall panel fracture zone height is projected to be 18t, or 252 feet, of which the lower two-thirds, or 168 feet, are capable of transmitting water. Therefore, the combined height of the mined longwall panel caved and fracture zones capable of transmitting water is projected to be a maximum of 238 feet.

As discussed in Section 5.3.2, the maximum crack depth in the Southern Panels and Sunset Trail mining areas is estimated to be 15 feet in terrains with slopes less than 30 percent, with depths up to 35 feet occurring locally in steep topography. For the South Prong channel near the western edge of longwall panel SS4, the maximum projected crack depth is 15 feet. Consequently, the combined maximum height of the caved and fractured zones and the maximum crack depth is 253 feet.

Based on previous mine plans and overburden thickness projections, the previous modeling evaluation indicated that no longwall panel subsidence impacts were projected with a minimum overburden thickness of 375 feet, leaving an estimated 122-foot “buffer” of unfractured bedrock remaining intact. It was not the intent of the previous analysis to indicate or specify that the 122-foot buffer was necessary or that longwall mining could not occur in overburden less than 375 feet. WWE does believe that it is prudent to have a “buffer” to reduce the possibility of a hydraulic connection between the ground surface and the mined longwall panels. We recommend that a factor of safety of 20 percent be added to the combined fracture height and crack depth total to yield the minimum overburden necessary to avoid a hydraulic connection. For example, if mining

at a thickness of up to 14 feet, then the minimum overburden cover should be 253 feet plus 20 percent, or about 304 feet.

This minimum overburden is directly a function of the mining height as shown above, and can be reduced if the longwall mining height is lowered. For example, if the mining height were to be reduced to 12 feet near the western end of longwall panel SS4, then the combined height of the caved and fracture zones capable of transmitting water is projected to be 204 feet ( $5t = 60'$ ;  $2/3(18t) = 144'$ ). Adding in the maximum projected crack depth of 15 feet yields a combined height of 219 feet, or 263 feet with the 20 percent “buffer.” Therefore, the mine can make operational decisions based on the actual overburden encountered in specific locations. We do not recommend that longwall mining occur where overburden thickness is not at least 250 feet, even with reduced mining height.

The current projection of minimum overburden over the Sunset Trail longwall panel is approximately 280 feet at the western end of longwall panel SS4. Should this projected overburden prove to be accurate, MCC can either shorten the longwall panel at a location where the overburden drops below approximately 300 feet or reduce the mining height in accordance with the actual overburden thickness.

Another factor that will help maintain a lack of hydraulic connection between the surface and the mined longwall panels is the presence of soft shales and claystones in the E-seam overburden that will increase the probability that the strata will warp rather than fracture during the subsidence process. The projected lack of hydraulic connection was confirmed as mining occurred in E-seam panel E2 without any adverse impacts to Dry Fork or any anomalous water inflows observed in the mine. With the proposed B-seam mining occurring below the E-seam, we do not foresee the potential for hydraulic connection between Dry Fork and the mine workings.

#### **11.4 Springs and Water-Bearing Zones**

MCC has produced the Spring and Stock Pond Location Map that covers the Southern Panels, Apache Rocks West, and Sunset Trail mining areas. Only a few springs in the West Elk Mine area indicate a source from a local bedrock water-bearing zone. Most springs likely have sources from local water-bearing zones in surficial material (debris flows, colluvium, and possibly alluvium).

In contrast to surface water containment structures, such as reservoirs, ponds, streams and ditches, springs and water-bearing zones may have water sources that are either in bedrock beneath the blanket of clay-rich surficial material (debris flows, alluvium, and colluvium), or have a source from within the surficial material. Subsidence may affect a spring or water-bearing zone source located in bedrock, whereas effects may or may not be expected where the spring source is within the surficial material. Tension cracks produced in sandstone bedrock during the subsidence process, for example, may divert water to a lower rock layer and therefore change the flow location. However, local water-bearing zones in permeable zones, which are interlayered with clay-rich zones (Wasatch clays) in the surficial deposit, may yield to tensile stresses without cracking. Therefore, spring flows are monitored for a few years (to account for seasonal variations) prior to any mining in the area. Monitoring data and field observations are provided each year in MCC’s Annual Hydrology Report.

## **11.5 Roads**

As was observed in the Apache Rocks and Box Canyon mining areas, effects from mine subsidence are typically limited to cracks that do not prevent passage on most of the access roads and drill roads in the Southern Panels mining area. Also, as expected, no effects from landslide movements or rockfalls have occurred, because the mining rockfall potential is mapped in the moderate-high category or lower, and rockfalls were observed to occur only in the high to very high rockfall category areas in the Box Canyon mining area.

No cracks have been observed in the soft, pliable alluvium, but a few cracks have occurred on the harder and more highly compacted Dry Fork access road, particularly in the area near the confluence of Deer Creek and Dry Fork, although all have been of a small extent. Observations along these roads are documented in the semi-annual Subsidence and Geologic Field Observations reports.

## **11.6 Buildings**

Baseline information on buildings, such as foundations, walls, chimneys, and roofs, has already been obtained on the Dry Fork Cow Camp in July 2004 (Dunrud 2004b) prior to any mining. A pre-mining survey of the Cow Camp structures was performed by West Elk Land Surveying in February 2006 and is included as Exhibit 73. The Minnesota Creek ditch rider's cabin is located near the headwaters of Dry Fork in the Dry Fork mining area. An exterior inspection of the cabin was performed in 2004 by the U.S. Forest Service and Agapito Associates, Inc. (Agapito, 2005). The structure was reported to be in average structural condition.

### **11.6.1 Lower Dry Fork Cow Camp**

The cabin exterior is approximately 13 feet wide, 20 feet long, and 8.5 feet high (the wall height). A lean-to 7 feet long and a porch 5.5 feet wide are located on the north and south ends of the cabin (see Figures 7 and 8, of Exhibit 60D for details). The outside walls are of a wood, board-and-bat construction.

The foundation, which is of rock and mortar construction (and an estimated 1½ feet thick), ranges from about 1 foot high in the back to 20 inches high in the front. The roof is covered with tin. The side windows, which measure 2 by 3 feet in outside dimension, are located in the approximate center of either wall.

Post-mining observations and measurements of the cabin following mining have been documented in the Subsidence and Geologic Field Observations Reports.

### **11.6.2 Minnesota Creek Ditch Rider's Cabin**

This cabin was built in the 1950's and is 24 feet 4 inches by 16 feet 4 inches single-story wood framed building. The cabin is located over the projected potential extended eastern end of E-seam longwall panel E6.

## **12.0 POSSIBLE SUBSIDENCE CONSEQUENCES**

Predicted subsidence impacts for the Southern Panels and Sunset Trail mining areas has been described in detail above. The greatest surface impacts are expected to occur along the precipitous slopes and cliffs that flank Minnesota Creek, Lick Creek, Deep Creek, and other tributaries. Though unlikely, the worst possible consequences foreseen are that cracks could locally form and be as much as 25 to 50 feet deep above chain pillars and barrier pillars in bedrock on the precipitous slopes, ridges, and/or cliffs that flank Minnesota Creek, Lick Creek, and other tributaries, and may locally accelerate the naturally-occurring rockfall and landslide process.

E-seam mining in longwall panel E2 has already occurred underneath Dry Fork with mining thickness near 14 feet and with overburden as little as 375 to 400 feet. No adverse impacts to the Dry Fork stream channel or flow were observed during or subsequent to mining. Since this case represented the worst-case scenario, the stream channels in the Dry Fork watershed are not expected to be adversely impacted, even with two-seam mining.

In the Sunset Trail mining area, conditions under the South Prong channel are expected to be similar to the Dry Fork channel in the South of Divide mining area. As noted in Section 5.3.2, reaches of South Prong underlain by bedrock are more susceptible to surface cracking. If this occurs away from the edge of the panel, then the crack will likely be short term and closed once the longwall mining progresses as discussed in Section 4.1. Surface cracks that persist are projected to be 5 to 15 feet deep and will not be hydraulically connected to the mine workings as discussed in Section 11.3.1

Based on subsidence observations by WWE (as discussed in Section 5.3.2), no cracks are expected to occur in either the alluvium in the Dry Fork, Lick Creek, and other tributaries or stock watering ponds and drainage diversion ditches. In addition, no cracks are predicted to occur in colluvium more than about ten feet thick.

### **13.0 POTENTIAL IMPACTS FROM LOCAL SEISMIC ACTIVITY**

Earth tremors have been recorded or felt by local residents in the Somerset area since the early 1960s. The tremors commonly are the result of coal mine bumps and rock bursts, which are spontaneous releases of strain energy in highly stressed mined/caved coal and rock. In the Somerset Mine area before closure, the bumps and rock bursts were common in room-and-pillar mining areas where stresses concentrated within isolated pillars and blocks of coal (called bump blocks). Earth tremors have continued sporadically in the Somerset Mine area since the mine was closed in the 1980s.

Tremors generated by bumps and rock bursts in the Somerset Mine area attain magnitudes that have shaken structures in the West Elk Mine area and have sometimes been felt by West Elk Mine personnel. These local tremors may affect, to a minor degree, underground workings, landslide or potential rockfall areas, particularly during prolonged periods of increased precipitation. It is noteworthy, however, that the Rulison nuclear shot in 1969, which produced a tremor with a Richter magnitude of 5.2 (the magnitude of energy released was many times greater than the magnitudes of any recorded bump or rock burst), did not affect the Somerset Mine. To our knowledge the Rulison nuclear shot did not trigger any landslides or rockfalls, nor did it impact reservoirs, ponds, or streams in the Southern Panels, Apache Rocks West, or Sunset Trail mining areas.

## **14.0 SUBSIDENCE CONTROL PLAN**

Longwall mining has been and is being used for extraction of the B-seam and E-seam in the West Elk Mine. Although longwall mining may initially induce more caving and fracturing of the roof rocks as compared to the room-and-pillar method due to the complete removal of coal in the panel, it offers the advantages of maximizing resource recovery. The longwall method also causes more uniform subsidence (full extraction of panel) and causes equilibrium conditions to be reached in a shorter period of time (i.e., there is no additional, lingering pillar crushing in panels).

### **14.1 Anticipated Effects**

Long-term impacts on the surface are predicted to be minimal above the longwall panels. The few surface cracks over the mined longwall panels that may occur are expected to close once the longwall face moves past the surface area of influence. Surface cracks present above the rigid chain or barrier pillars or mine boundaries may remain open for many years where permanent tensile strains remain after longwall mining is completed. However, several hundred feet of rock will typically exist between any mine-induced surface fractures and the upper part of any longwall mine-induced fractures above the caved zone in the longwall mining panels. Therefore, from a practical standpoint, no interconnection between the surface fractures and the longwall mine workings is anticipated. Again, under a worst-case scenario, if a surface fracture were to occur concurrently within an area controlled by faults or bedrock lineaments, there could be interconnection between adjacent sandstones. However, even under these conditions, the fractures would not extend through the claystones and shales present in the overburden.

Minnesota Reservoir is located well outside of the area of longwall mining influence of the projected B-seam and E-seam panels for the Southern Panels, Apache Rocks West, and Sunset Trail mining areas and, therefore, will not be affected by longwall mining.

### **14.2 Reduction Measures (Underground)**

Underground measures that may be taken to reduce surface strains above the longwall panel chain pillars could include: (1) designing the pillars to yield and crush after mining (thus minimizing humps in the subsidence profile), and/or (2) planning a rapid and uniform longwall mining rate. Any plans to reduce chain pillar dimensions in order to reduce subsidence impacts must, of course, be balanced with health and safety conditions in the mine. Plans for a rapid and uniform mining rate are affected by market demands (or lack thereof) for a constant, high volume of coal.

### **14.3 Development Mining**

Although subsidence is primarily a result of the secondary recovery of coal from a longwall coal panel, subsidence-type features may occur when developing main entries/roadways under shallow, unconsolidated and saturated cover. Such was the case in October 2020 when developing main entries under South Prong Creek. To avoid similar issues in the future, MCC has performed an analysis of the minimum depth of cover required for development mining in the West Elk Mine to avoid the potential for this type of surface subsidence impacts. WWE has included this Technical Memo as Appendix A to this exhibit.



## 15.0 SUMMARY AND CONCLUSIONS

The measured subsidence parameters over the B-seam and E-seam longwall panels at the West Elk Mine has fallen within the range of predicted subsidence parameters developed from the original subsidence data collected over the Northwest B-seam longwall panels. In addition, the annual subsidence field studies have observed subsidence effects at the expected locations and consistent with the projections resulting from the modeling completed in the Exhibit 60 series.

The subsidence parameters also fall within the range of those measured and calculated by Dunrud in four different coal mining areas in Colorado, Utah, and Wyoming (Dunrud 1987). The subsidence parameters also are consistent with the appropriate National Coal Board graphs (Figures 4 and 5).

Results of subsidence measurements and analyses in the West Elk subsidence monitoring area also are in general agreement with the computer modeling programs developed in the Eastern United States. These favorable comparative results calibrated by West Elk subsidence measurements, therefore, give added assurance that the subsidence parameters projected for the Southern Panels, Apache Rocks West, and Sunset Trail mining areas are realistic and correct.

Specific conclusions are as follows:

1. Maximum vertical displacement (subsidence), tilt, and horizontal strain predicted for longwall mining in the Southern Panels, Apache Rocks West, and Sunset Trail mining areas are likely to be conservative values. Subsidence monitoring data collected after mining of longwall panels E1 through E3 show that actual subsidence was at the lower end of the predicted range. Similarly, the computer model projections overestimated the subsidence over panel E1, while accurately predicting subsidence along Dry Fork over panels E2 and E3.
2. Mining of the longwall mining panels in the Southern Panels mining area will not impact Minnesota Reservoir. The reservoir is completely out of the area of mining influence. All mine workings, including E-seam and B-seam longwall panels are 500 to 600 feet farther away from the reservoir footprint, using even a 45-degree angle of draw. Mining in panels E2 and E3 occurred without any adverse impacts to the reservoir. In addition, Minnesota Reservoir is the outside area of influence for two-seam mining in the Apache Rocks West mining area.
3. No cracks have been observed in the alluvium in any of the drainages of the Dry Fork of Minnesota Creek, or Deep Creek. The composition and thickness of the alluvium in these drainages make it unlikely for cracks to form in the stream channels of drainages in the Southern Panels, Apache Rocks West, and Sunset Trail mining areas. Two-seam mining under Dry Fork will produce some of the largest projected subsidence parameters experienced at the West Elk Mine. However, based on the lack of adverse impacts due to the E-seam mining, the B-seam panels B26 to B29 are not anticipated to impact the channel due, in part, to the greater overburden thickness.

4. The South Prong channel in the Sunset Trail mining area overlays panel SS4, where the overburden is projected to be roughly 300 feet at the western end of the panel. The potential for hydraulic connection between a surface crack and fractures from the mine are negligible when overburden is 300 feet or more. If actual conditions show the overburden to be less than 300 feet, then the mining height should be reduced to continue to minimize the risk of a hydraulic connection forming.
5. Mining impacts on rockfalls were not observed during annual subsidence observations in the Apache Rocks and Box Canyon mining areas over six years (1999 to 2004 inclusive), in areas where the estimated rockfall potential was moderate to high. The highest estimated rockfall potential is classified as moderate to high in the Southern Panels mining area, and many of these are located in areas where no mining is currently planned. Consequently, the natural rockfall process is not expected to be significantly accelerated by longwall mining.
6. The landslides that are located north and south of Minnesota Reservoir and above the northern part of E-seam longwall panel E9, are not expected to be noticeably impacted by subsidence or seismic activity caused by longwall mining. Based on field observations, the major finding is that landslide movement occurs in response to moisture and ground saturation, and is not noticeably affected by subsidence or any mine-related seismic activity caused by longwall mining beneath or near the landslides.
7. There is no historical record from annual observations in the West Elk Mine area regarding effects of mining on springs and local water-bearing zones, with sources in either surficial material or bedrock. These observations are documented in the Annual Hydrology Reports.
8. Small cracks have occurred on the hard, compacted access roads following longwall mining. However, these cracks have never affected use of the roads.

## 16.0 REFERENCES

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## TABLES

**TABLE 1**  
**MAXIMUM SUBSIDENCE PARAMETERS**  
**FROM WEST ELK MINE SUBSIDENCE MONITORING NETWORK**

Parameter	Longitudinal Profile So. End 1 NW LW	Longitudinal Profile No. End 1 NW LW	Transverse Profile Above 2,3 NW LW
W/d	750/1240=0.6	750/1350=0.56	2 NW: 750/1000=0.75 3 NW: 750/900=0.83
$a_{cp}=S_{cp}/t$	N/A	N/A	0.20 to 0.35
$a=S_m/t$	6.94/12=0.58	6.06/11.5=0.53	2 NW: 0.62 3 NW: 0.58
$S_m/d$	0.005597	0.004489	2 NW: 0.00729 3 NW: 0.00762
$S_m/d^2$	0.000004514	0.000003325	2 NW: 0.00000729 3 NW: 0.00000847
$M_m$	0.015 (2.7· $S_m/d$ )	0.014 (3.1· $S_m/d$ )	2 NW: 0.014 3 NW: 0.021
$C_m^{(1)}$	0.000065 (14.4· $S_m/d^2$ )  -0.000111 (-24.6· $S_m/d^2$ )	0.000060 (18.0· $S_m/d^2$ )  -0.000066 (-19.9· $S_m/d^2$ )	2 NW: 0.00022 3 NW: 0.00014  2 NW: -0.00025 3 NW: -0.00012
$E_m$	0.0070 (1.25· $S_m/d$ )  -0.0047 (-0.8· $S_m/d$ )	0.0058 (1.3· $S_m/d$ )  -0.0009 (-0.2· $S_m/d$ )	2 NW: 0.0102 3 NW: 0.0085  2 NW: -0.0236 3 NW: -0.0307
Maximum Crack Depth <sup>(2)</sup>	80 feet	100 feet	50 feet
Break Angle <sup>(3)</sup>	32percent Slope - -9° Slope in same Direction as tilt	3° 42percent Slope - Slope in opposite Direction to tilt	—
Angle of Draw <sup>(3)</sup>	17° <sup>(4)</sup>	15° <sup>(4)</sup>	—

**Notes:**

- (1) Numerical curvature values are in radians per foot (rad/ft).
- (2) Maximum crack depth is projected for hard, brittle sandstones; depth is expected to be much less, or non-existent, in soft, ductile shales and claystones.
- (3) Measurement from vertical reference.
- (4) Measurement takes into account influence of development entries, chain pillars, and prior F-seam mining.

**TABLE 2**  
**MAXIMUM SUBSIDENCE PARAMETERS FOR**  
**SOUTHERN PANELS MINING AREA<sup>(1)</sup>**

		E-Seam Mining		B-Seam Mining		Sum of E and B-Seam Mining	
Parameter		Panels E1 - E9, E14 (t = 9 to 14 ft)		Panels B26 - B29 (t = 9 to 14 ft)		Sum of E & B Panels	
W/d: <sup>(2)</sup>	Max	E1-E5: 1080 / 400	2.70	B26-29: 1080 / 600	1.80		
	Min	1080 / 1425	0.76	1080 / 1500	0.72		
	Max	E6-E9, E14: 1080 / 370	2.92				
	Min	1080 / 1200	0.90				
		t = 9 ft	t = 14 ft	t = 9 ft	t = 14 ft	t = 9 ft	t = 14 ft
$S_{cp} = a_{cp} \cdot t^{(3)}$  ( $a_{cp} = S_{cp}/t$ )	Max	2.7	4.2	2.7	4.2	--	--
	Min	0.9	1.4	0.9	1.4	--	--
	Max	0.3	0.3	0.3	0.3	--	--
	Min	0.1	0.1	0.1	0.1	--	--
$S_m = a \cdot t^{(4)}$  ( $a = S_m/t$ )	Max	7.2	11.2	7.2	11.2	14.4	22.4
	Min	5.4	8.4	5.4	8.4	10.8	16.8
	Max	0.8	0.8	0.8	0.8	--	--
	Min	0.6	0.6	0.6	0.6	--	--
$S_m/d^{(5)}$	Max	0.019	0.030	0.012	0.019	0.031	0.049
	Min	0.004	0.006	0.004	0.006	0.007	0.011
$M_m$ (2.2 to 2.3 $S_m/d$ ) <sup>(6)</sup>	Max	0.045	0.070	0.028	0.043	0.054	0.084
	Min	0.008	0.013	0.008	0.012	0.010	0.016
$E_m$ (in terms of $S_m/d$ ) <sup>(7)</sup> (1.2 to 1.4 $S_m/d$ )	Max	0.027	0.042	0.017	0.026	0.044	0.069
	Min	0.005	0.007	0.004	0.007	0.009	0.014
$-E_m$ (in terms of $S_m/d$ ) <sup>(7)</sup> (-1.2 to -1.5 $S_m/d$ )	Max	-0.029	-0.045	-0.018	-0.028	-0.047	-0.073
	Min	-0.005	-0.007	-0.004	-0.007	-0.009	-0.014
Maximum Crack Depth <sup>(8)</sup>	1	Max	10	15	10	15	10
		Min	5	5	5	5	5
	2	Max	25	35	25	35	25
		Min	10	15	10	15	10
Break Angle <sup>(9)</sup>	Max	5°	5°	5°	5°	5°	5°
	Min	0°	0°	0°	0°	0°	0°
Angle of Draw <sup>(9)</sup>	Max	19°	19°	19°	19°	19°	19°
	Min	14°	14°	14°	14°	14°	14°

<sup>(1)</sup> Maximum tilt and strain parameters apply only to ground surfaces with slopes less than 30 percent; values may be greater on slopes steeper than 30 percent.

<sup>(2)</sup> All panels are numbered according to planned panel identifications.

<sup>(3)</sup> Subsidence and subsidence factor above chain pillars.

<sup>(4)</sup> Subsidence (maximum vertical displacement) above longwall panel centers, based on planned coal extraction thickness listed.

<sup>(5)</sup> Ratio of the range of maximum vertical displacement to overburden depth range for the longwall panels.

<sup>(6)</sup> Maximum range of tilt in terms of  $S_m/d$ ; values of 2.2 to 2.3  $S_m/d$  are obtained from the graph in Figure 5.

<sup>(7)</sup> Maximum range of horizontal strain in terms of  $S_m/d$ ; values for tensile (positive) strain of 1.2 to 1.4  $S_m/d$  and compressive (negative) strain of -1.2 to -1.5  $S_m/d$  are obtained from the graph in Figure 5.

<sup>(8)</sup> Maximum crack depth (in feet) in bedrock predicted to locally occur on or near steep slopes and ledges in the Minnesota Creek and Lick Creek drainage areas and above barrier pillars and rigid chain (gate road) pillars. The first depth range (1) is for bedrock sloping less than, or equal to, 30 percent; the second depth range (2) is for slopes more than 30 percent. Add 5 to 15 feet where thick, brittle sandstones occur in ridges and near cliffs. No cracks are predicted to occur in alluvium. No cracks are predicted to occur at the surface of colluvium thicker than about 10 feet.

<sup>(9)</sup> Angle measured from a vertical reference.

**TABLE 3**  
**MAXIMUM SUBSIDENCE PARAMETERS FOR**  
**APACHE ROCKS WEST MINING AREA<sup>(1)</sup>**

E-Seam Mining				B-Seam Mining			Sum of E and B-Seam Mining			
Parameter		Panels E10 - E12 (t = 10 to 14 ft)			Panels B12 - B13A (t = 12 ft)			Sum of E & B Panels		
W/d: <sup>(2)</sup>	Max	E10-E12:	1080 / 400	2.70	B12-13A:	950 / 750	1.27			
	Min		1080 / 1100	0.98		950 / 1300	0.73			
		t = 10 ft		t = 14 ft	t = 12 ft			t = 10 ft	t = 14 ft	
S <sub>cp</sub> = a <sub>cp</sub> • t <sup>(3)</sup>	Max	4.0		5.6	4.8			--	--	
	Min	1.0		1.4	1.2			--	--	
(a <sub>cp</sub> =S <sub>cp</sub> /t)	Max	0.4		0.4	0.4			--	--	
	Min	0.1		0.1	0.1			--	--	
S <sub>m</sub> = a • t <sup>(4)</sup>	Max	8.0		11.2	9.6			17.6	20.8	
	Min	6.0		8.4	7.2			13.2	15.6	
(a = S <sub>m</sub> /t)	Max	0.8		0.8	0.8			--	--	
	Min	0.6		0.6	0.6			--	--	
S <sub>m</sub> /d <sup>(5)</sup>	Max	0.020		0.028	0.013			0.033	0.041	
	Min	0.005		0.008	0.006			0.011	0.013	
M <sub>m</sub> (2.2 to 2.3 S <sub>m</sub> /d) <sup>(6)</sup>	Max	0.046		0.064	0.029			0.055	0.077	
	Min	0.012		0.017	0.012			0.014	0.020	
E <sub>m</sub> (in terms of S <sub>m</sub> /d) <sup>(7)</sup> (1.2 to 1.4 S <sub>m</sub> /d)	Max	0.028		0.039	0.018			0.046	0.057	
	Min	0.007		0.009	0.007			0.013	0.016	
-E <sub>m</sub> (in terms of S <sub>m</sub> /d) <sup>(7)</sup> (-1.2 to -1.5 S <sub>m</sub> /d)	Max	-0.030		-0.042	-0.019			-0.049	-0.061	
	Min	-0.007		-0.009	-0.007			-0.013	-0.016	
Maximum Crack Depth <sup>(8)</sup>	1	Max	100		100	100			100	100
		Min	50		50	50			50	50
	2	Max	150		150	150			150	150
		Min	75		75	75			75	75
Break Angle <sup>(9)</sup>		Max	5°		5°	5°			5°	5°
		Min	0°		0°	0°			0°	0°
Angle of Draw <sup>(9)</sup>		Max	19°		19°	19°			19°	19°
		Min	14°		14°	14°			14°	14°

<sup>(1)</sup> Maximum tilt and strain parameters apply only to ground surfaces with slopes less than 30 percent; values may be greater on slopes steeper than 30 percent.

<sup>(2)</sup> All panels are numbered according to planned panel identifications.

<sup>(3)</sup> Subsidence and subsidence factor above chain pillars.

<sup>(4)</sup> Subsidence (maximum vertical displacement) above longwall panel centers, based on planned coal extraction thickness listed.

<sup>(5)</sup> Ratio of the range of maximum vertical displacement to overburden depth range for the longwall panels.

<sup>(6)</sup> Maximum range of tilt in terms of  $S_m/d$ ; values of 2.2 to 2.3  $S_m/d$  are obtained from the graph in Figure 5.

<sup>(7)</sup> Maximum range of horizontal strain in terms of  $S_m/d$ ; values for tensile (positive) strain of 1.2 to 1.4  $S_m/d$  and compressive (negative) strain of -1.2 to -1.5  $S_m/d$  are obtained from the graph in Figure 5.

<sup>(8)</sup> Maximum crack depth (in feet) in bedrock predicted to locally occur on or near steep slopes and ledges in the Minnesota Creek and Lick Creek drainage areas and above barrier pillars and rigid chain (gate road) pillars. The first depth range (1) is for bedrock sloping less than, or equal to, 30 percent; the second depth range (2) is for slopes more than 30 percent. Add 5 to 15 feet where thick, brittle sandstones occur in ridges and near cliffs. No cracks are predicted to occur in alluvium. No cracks are predicted to occur at the surface of colluvium thicker than about 10 feet.

<sup>(9)</sup> Angle measured from a vertical reference.



**TABLE 4**  
**MAXIMUM SUBSIDENCE PARAMETERS FOR**  
**SUNSET TRAIL MINING AREA<sup>(1)</sup>**

Parameter		Panels SS1 - SS4 (t = 9 to 14 ft)		
W/d: <sup>(2)</sup>	Max	SS1	1080 / 770	1.40
	Min		1080 / 1220	0.89
	Max	SS2	1080 / 650	1.66
	Min		1080 / 1260	0.86
	Max	SS3	1080 / 390	2.77
	Min		1080 / 1250	0.86
	Max	SS4	1080 / 350	3.09
	Min		1080 / 1100	0.98
		t = 9 ft		t = 14 ft
$S_{cp} = a_{cp} \bullet t$ <sup>(3)</sup>	Max	2.7		4.2
	Min	0.9		1.4
$(a_{cp}=S_{cp}/t)$	Max	0.3		0.3
	Min	0.1		0.1
$S_m = a \bullet t$ <sup>(4)</sup>  (a = $S_m/t$ )	Max	7.2		11.2
	Min	5.4		8.4
	Max	0.8		0.8
	Min	0.6		0.6
$S_m/d$ <sup>(5)</sup>	Max	0.021		0.032
	Min	0.004		0.007
$M_m$ (2.2 to 2.3 $S_m/d$ ) <sup>(6)</sup>	Max	0.047		0.074
	Min	0.009		0.015
$E_m$ (in terms of $S_m/d$ ) <sup>(7)</sup> (1.2 to 1.4 $S_m/d$ )	Max	0.029		0.045
	Min	0.005		0.008
$-E_m$ (in terms of $S_m/d$ ) <sup>(7)</sup> (-1.2 to -1.5 $S_m/d$ )	Max	-0.031		-0.048
	Min	-0.005		-0.008
Maximum Crack Depth <sup>(8)</sup>	1	Max	10	
		Min	5	
	2	Max	35	
		Min	15	
Break Angle <sup>(9)</sup>	Max	5°		5°
	Min	0°		0°
Angle of Draw <sup>(9)</sup>	Max	19°		19°
	Min	14°		14°

<sup>(1)</sup> Maximum tilt and strain parameters apply only to ground surfaces with slopes less than 30 percent; values may be greater on slopes steeper than 30 percent.

<sup>(2)</sup> All panels are numbered according to planned panel identifications. Because the tables provides for the full range of values, there is no need to distinguish between Layouts A and B.

<sup>(3)</sup> Subsidence and subsidence factor above chain pillars.

<sup>(4)</sup> Subsidence (maximum vertical displacement) above longwall panel centers, based on planned coal extraction thickness listed.

<sup>(5)</sup> Ratio of the range of maximum vertical displacement to overburden depth range for the longwall panels.

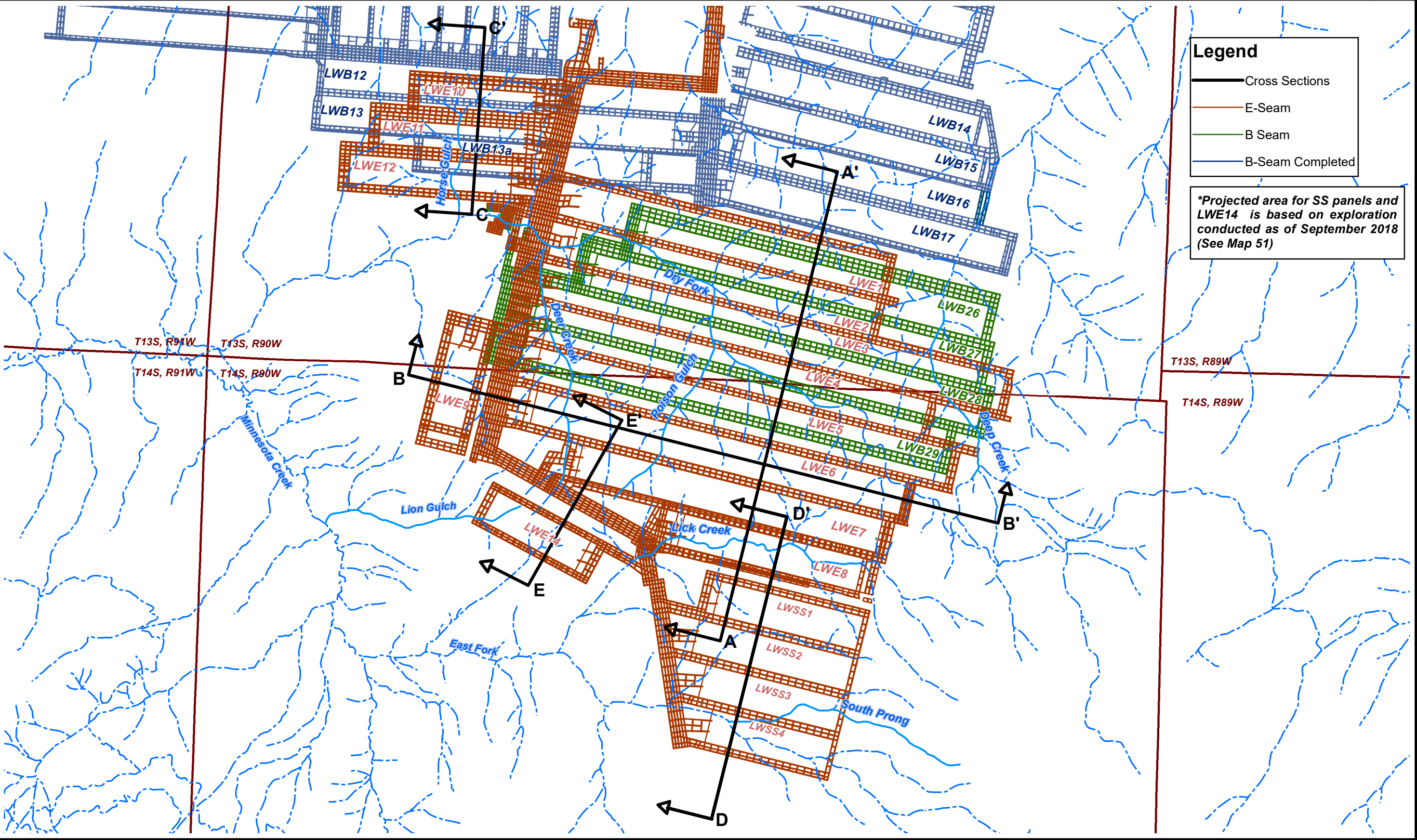
<sup>(6)</sup> Maximum range of tilt in terms of  $S_m/d$ ; values of 2.2 to 2.3  $S_m/d$  are obtained from the graph in Figure 5.

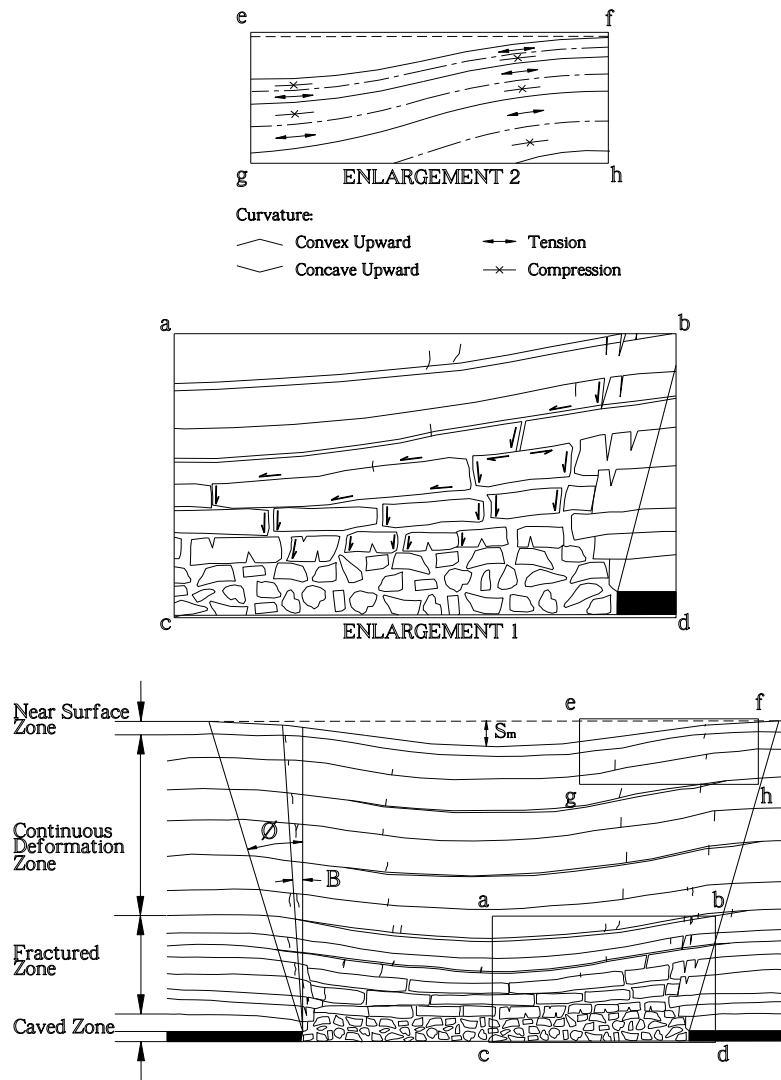
<sup>(7)</sup> Maximum range of horizontal strain in terms of  $S_m/d$ ; values for tensile (positive) strain of 1.2 to 1.4  $S_m/d$  and compressive (negative) strain of -1.2 to -1.5  $S_m/d$  are obtained from the graph in Figure 5.

<sup>(8)</sup> Maximum crack depth (in feet) in bedrock predicted to locally occur on or near steep slopes and ledges in the Minnesota Creek and Lick Creek drainage areas and above barrier pillars and rigid chain (gate road) pillars. The first depth range (1) is for bedrock sloping less than, or equal to, 30 percent; the second depth range (2) is for slopes more than 30 percent. Add 5 to 15 feet where thick, brittle sandstones occur in ridges and near cliffs. No cracks are predicted to occur in alluvium. No cracks are predicted to occur at the surface of colluvium thicker than about 10 feet.

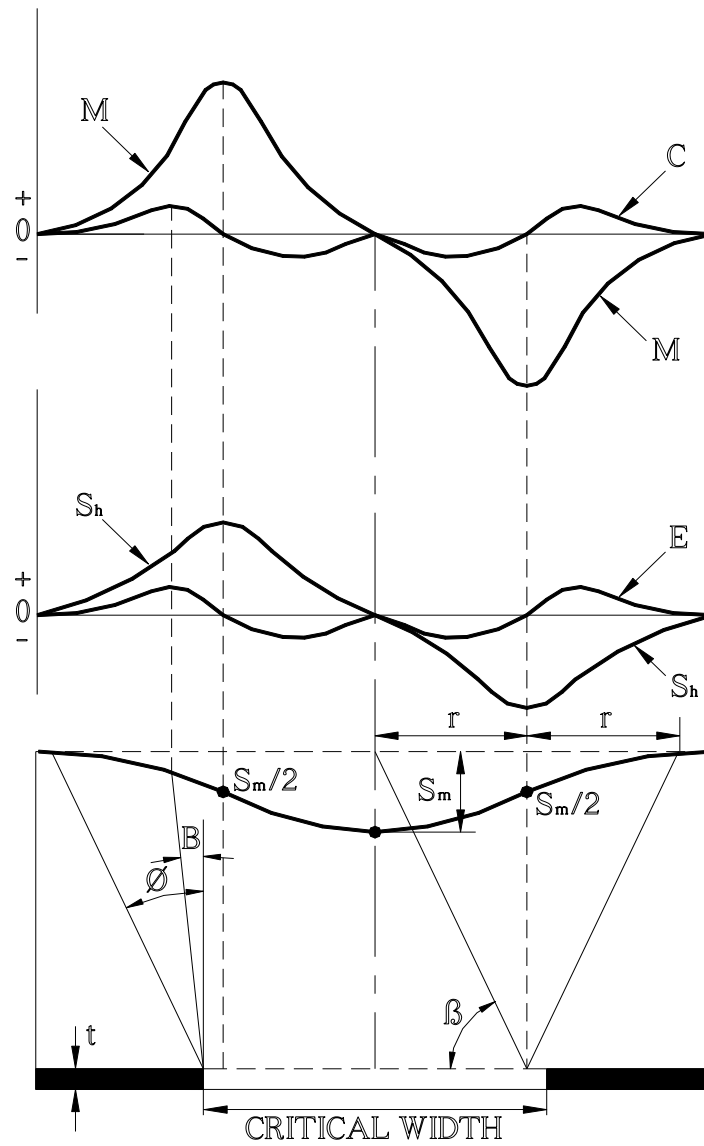
<sup>(9)</sup> Angle measured from a vertical reference.

## FIGURES

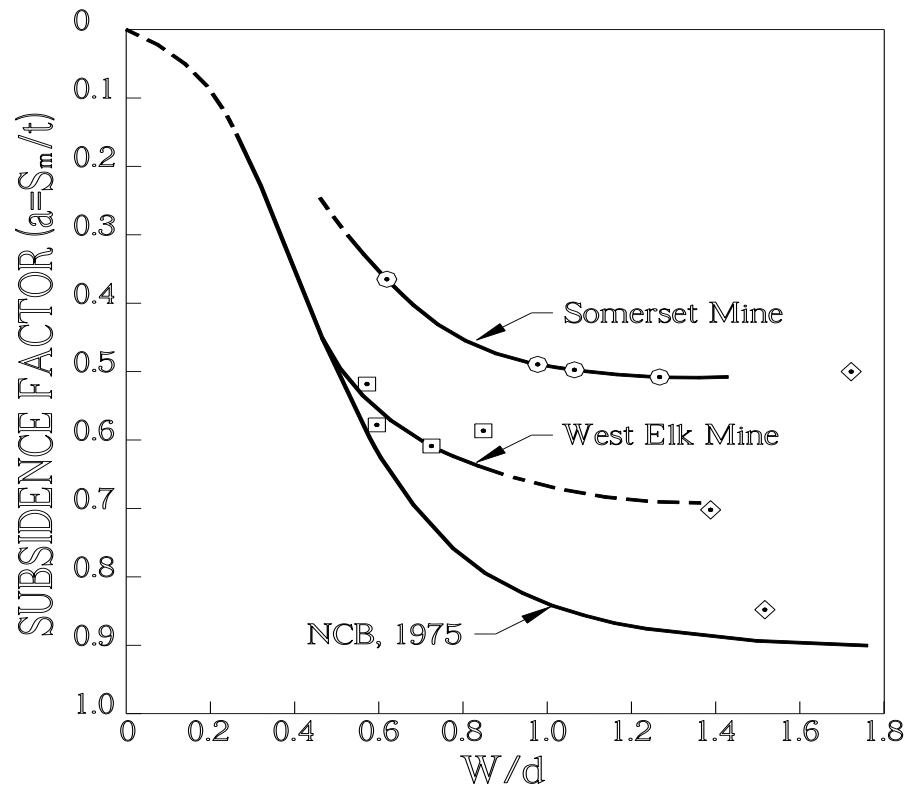




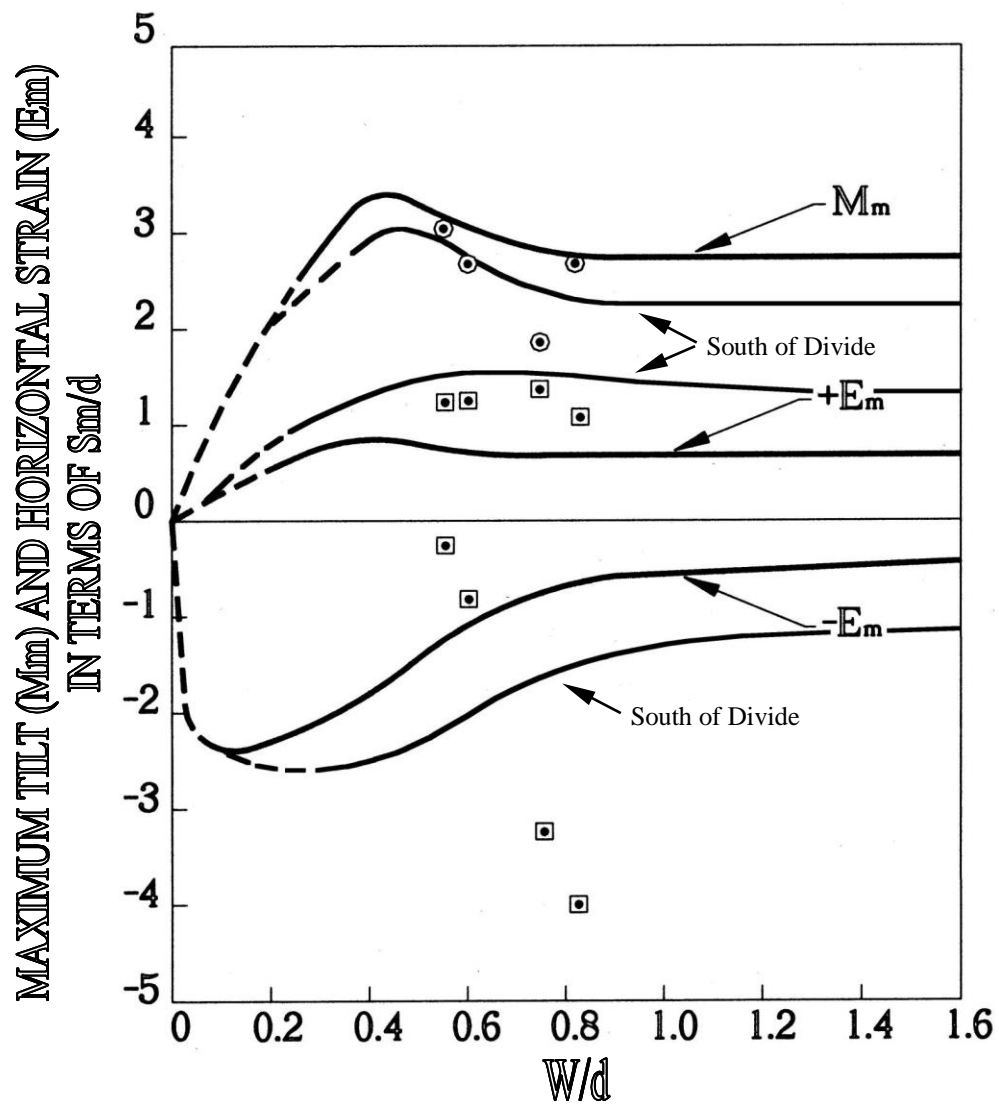
**Figure 2.** Conceptual diagram showing subsidence processes shortly after longwall mining (dynamic state). Enlargement shows some possible water flow directions in the fractured zone along fractures and separated bedding planes within the fractured zone. Enlargement 2 shows deflections of material in the near-surface and continuous-deformation zones and resulting tilt, curvature, and strain.



**Figure 3.** Diagram showing subsidence profile and parameters for a mining panel of critical width. The parameters are maximum vertical displacement ( $S_m$ ), horizontal displacement ( $S_h$ ), tilt (M), curvature (C), strain (E), angle of draw ( $\phi$ ), break angle (B), radius (r), and angle of major influence ( $\beta$ ).

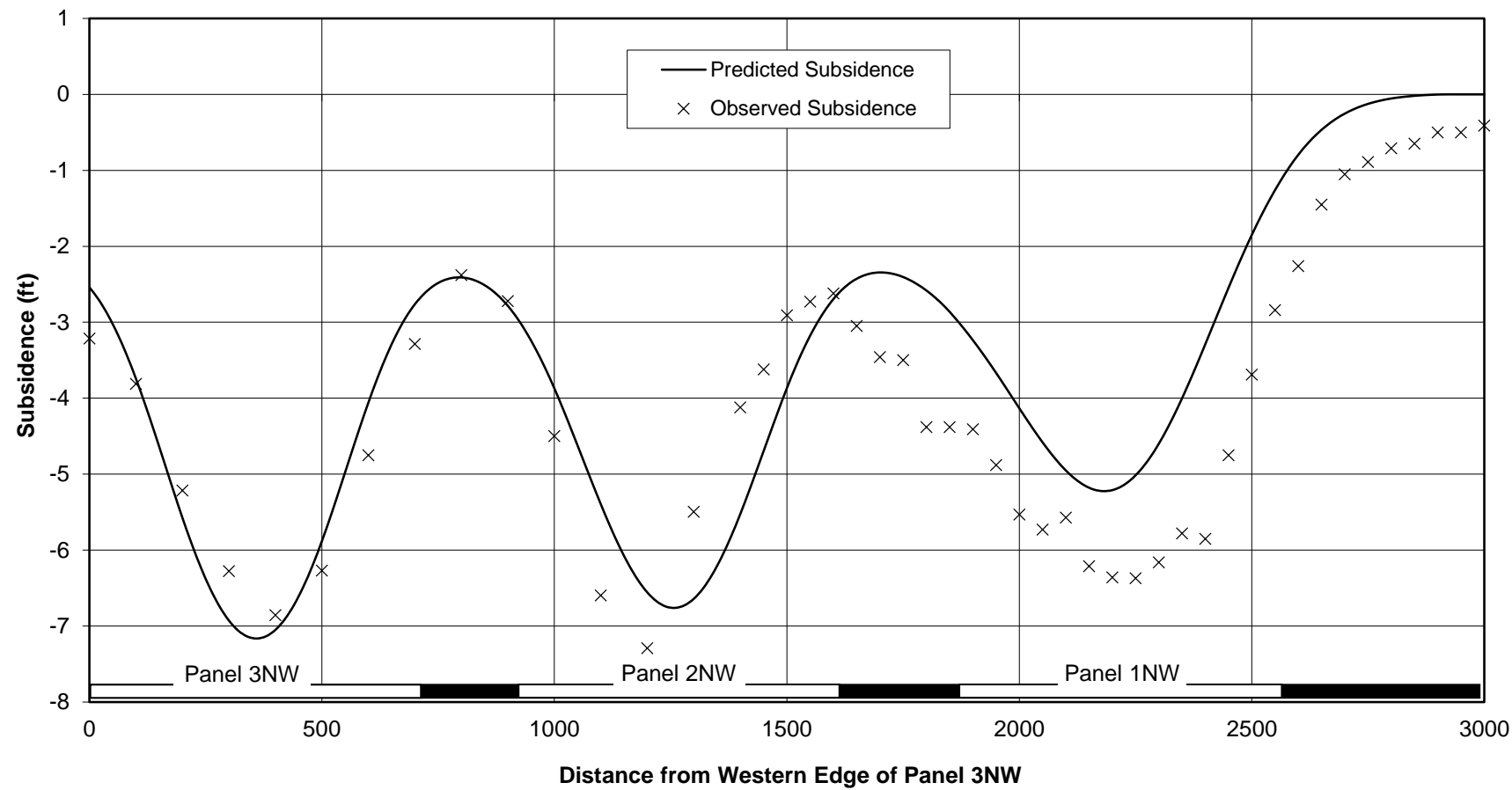


**Figure 4.** Graph showing subsidence factors ( $a = S_m/t$ ) versus mining panel width to depth ratios ( $W/d$ ) for the West Elk longwall mine (squares), 1972 to 1976 Somerset room-and-pillar mine (circles), and the York Canyon, New Mexico longwall mine (diamonds), along with the average National Coal Board (NCB) longwall curve. Topographic effects on subsidence factors for the York Canyon, New Mexico longwall mining area (upper point of measurement was in a deep draw; middle point was on an isolated ridge; lower point is maximum for area).



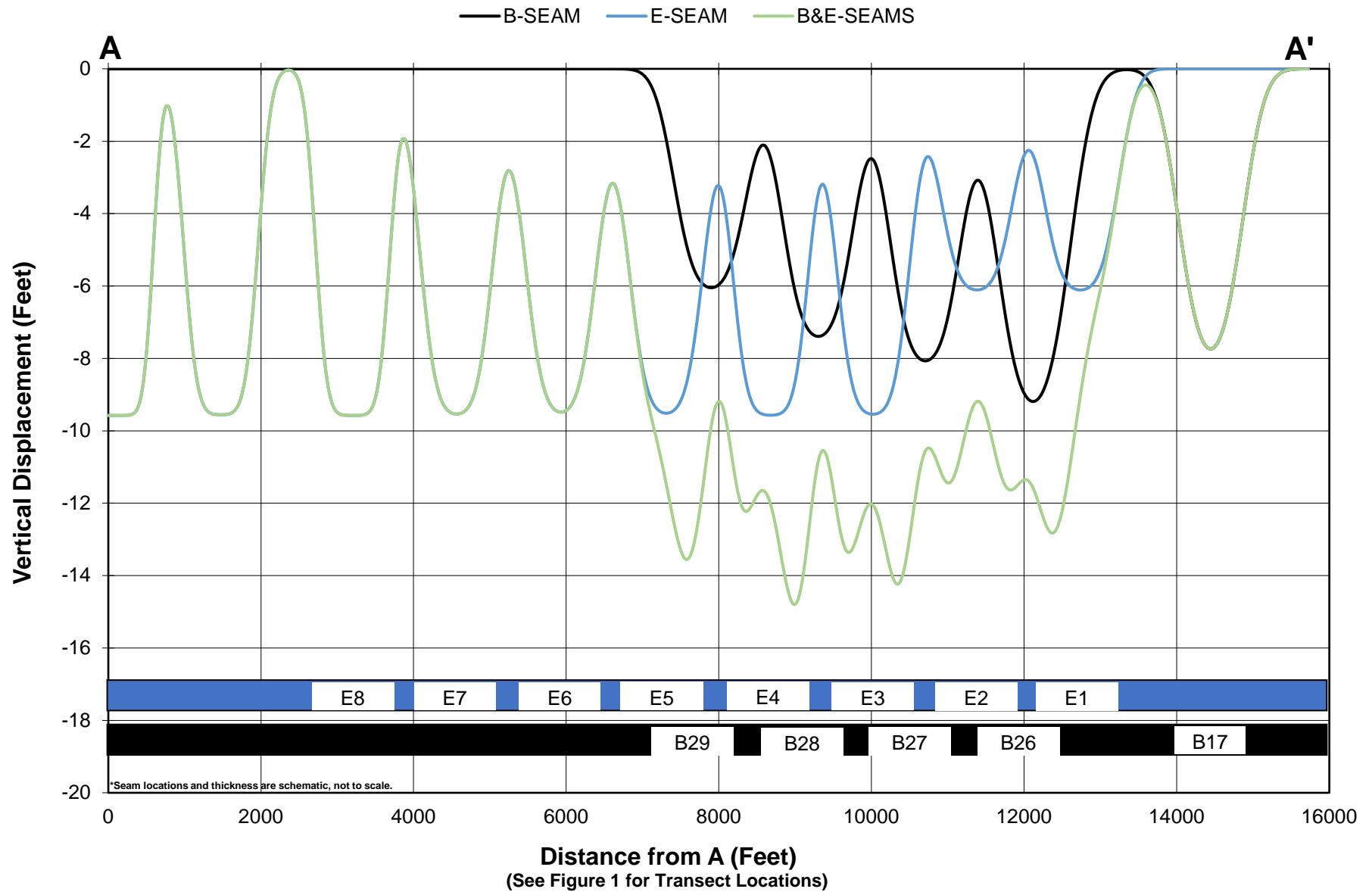
**Figure 5.** Graph showing maximum tilt ( $M_m$ ) and horizontal strain ( $E_m$ ) versus the mining panel width to depth ratio ( $W/d$ ). Tilt (circles) and horizontal strain (squares) for the West Elk Mine subsidence monitoring network are shown with the average National Coal Board (1975) longwall curves. New curves were developed for the South of Divide and Dry Fork mining areas.

**FIGURE 6**  
**COMPARISON OF MODEL PREDICTED VS OBSERVED SUBSIDENCE<sup>1</sup>**

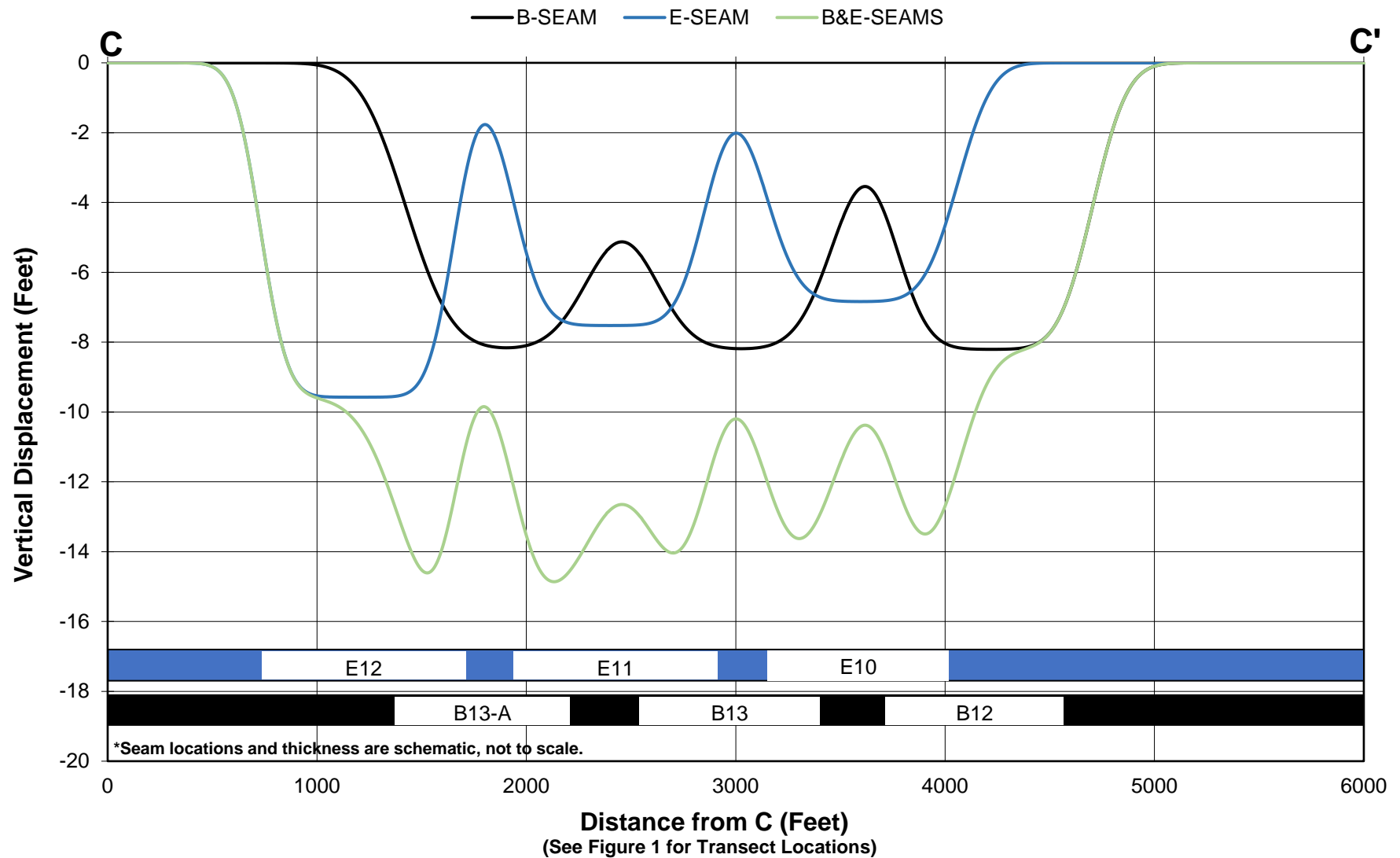




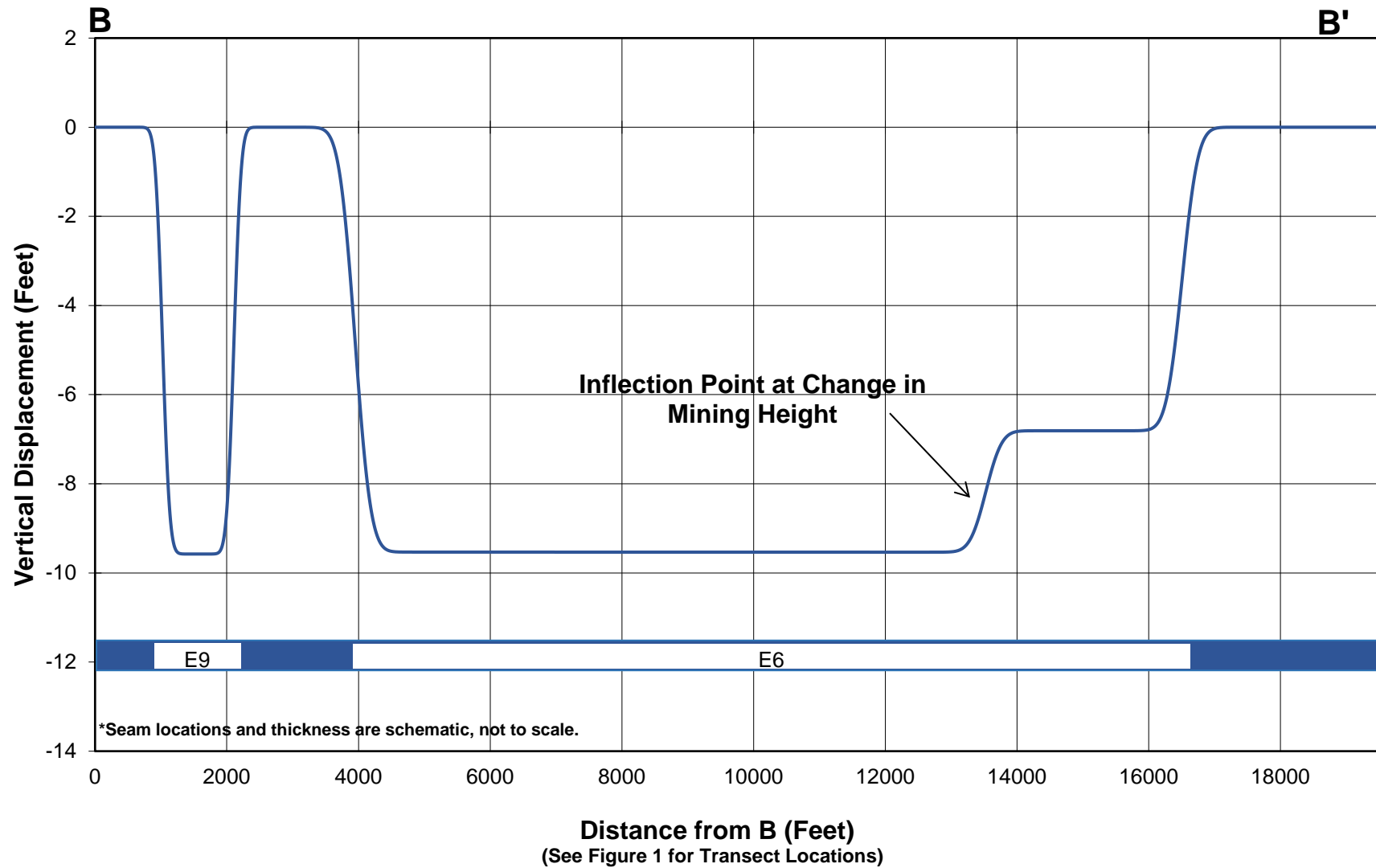
**Figure 7**  
**Panels E8 through E1 & B29 through B17 - Vertical Displacement**



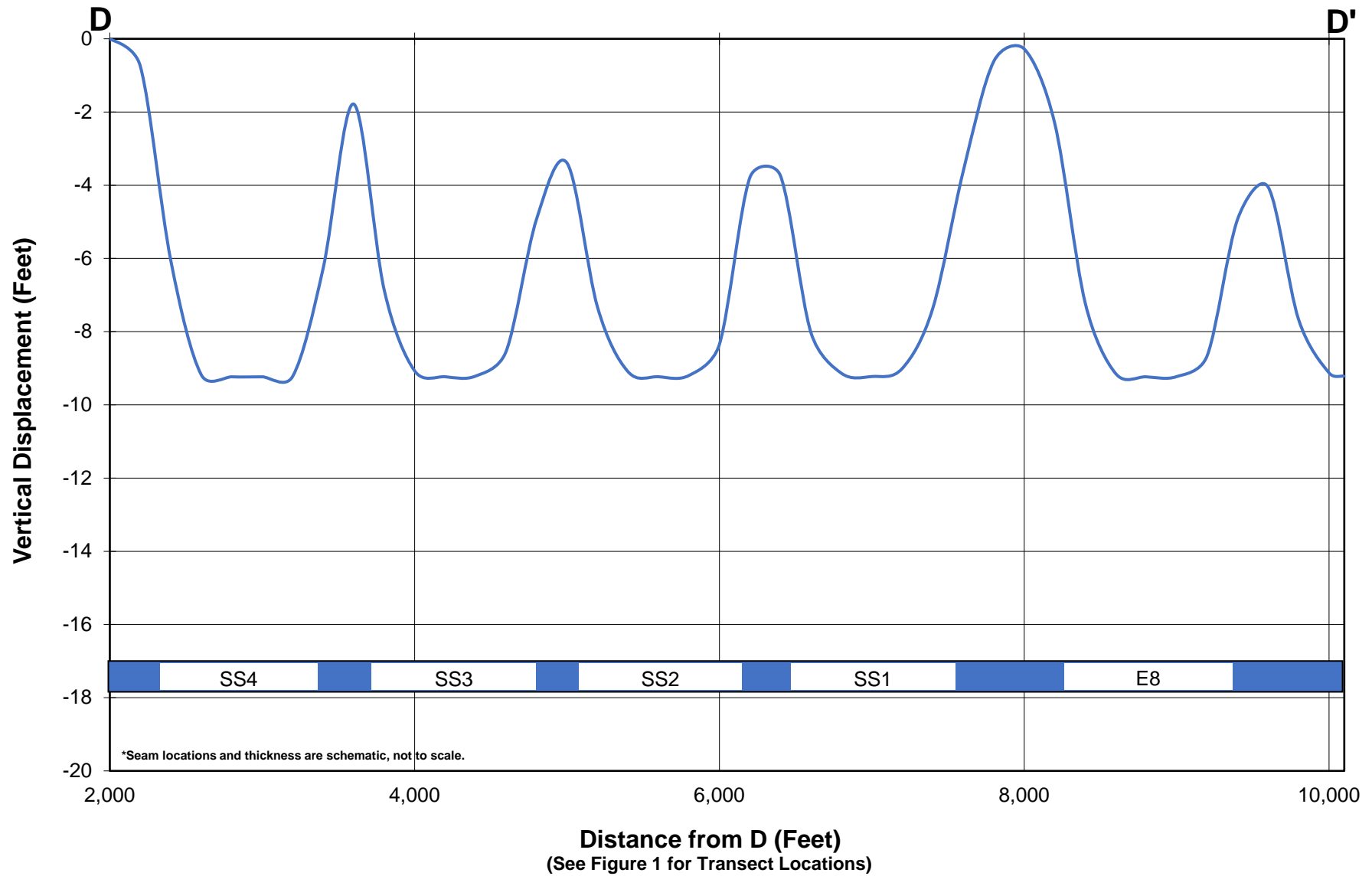
**Figure 7A**  
**Panels B13-A through B12 & E12 through E10 Vertical Displacement**



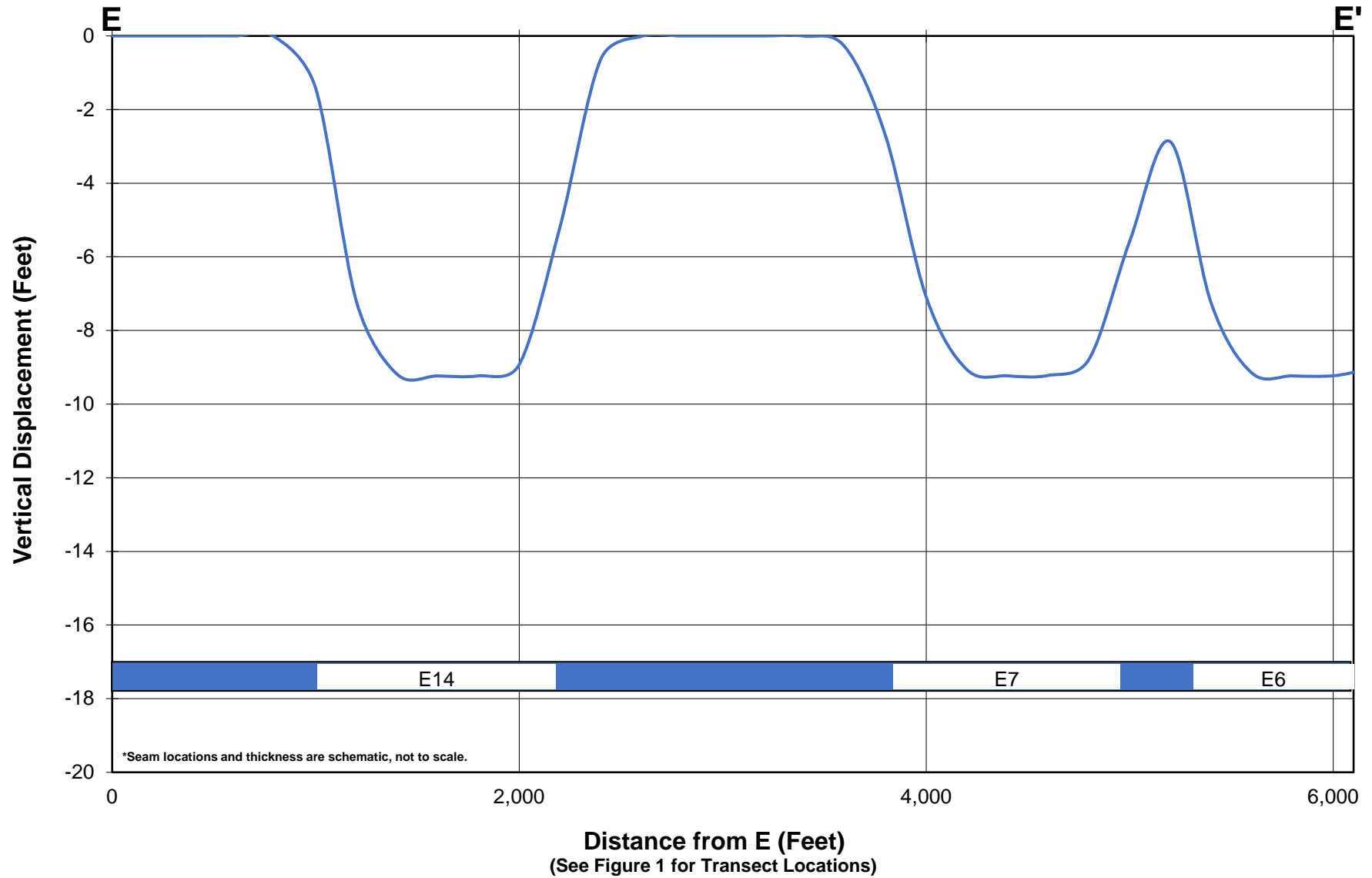
**Figure 8**  
**Panel E9 Traverse & Panel E6 Longitudinal Profile of Vertical Displacement**

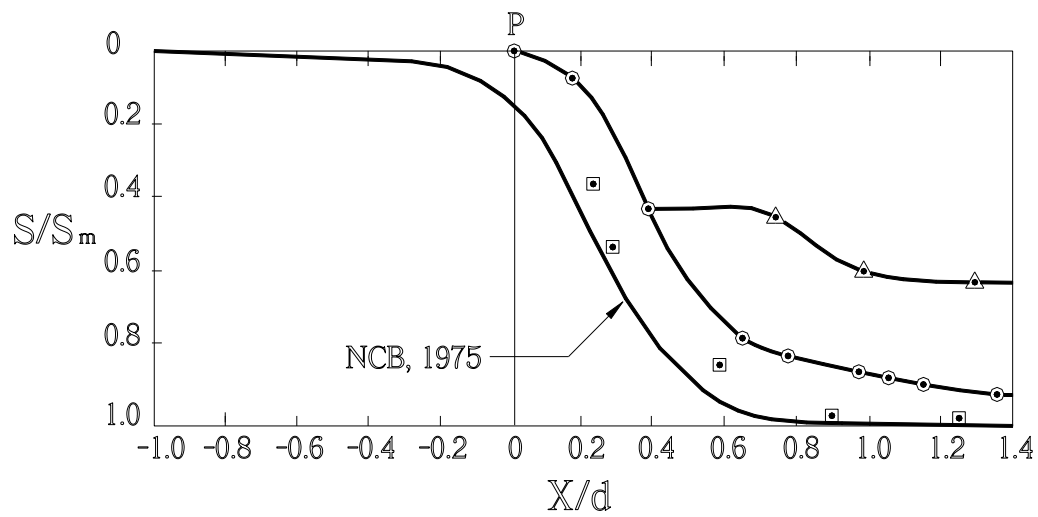


**Figure 9**  
**Panels SS4 through E8 - Vertical Displacement**



**Figure 10**  
**Panels E14 through E6 - Vertical Displacement**



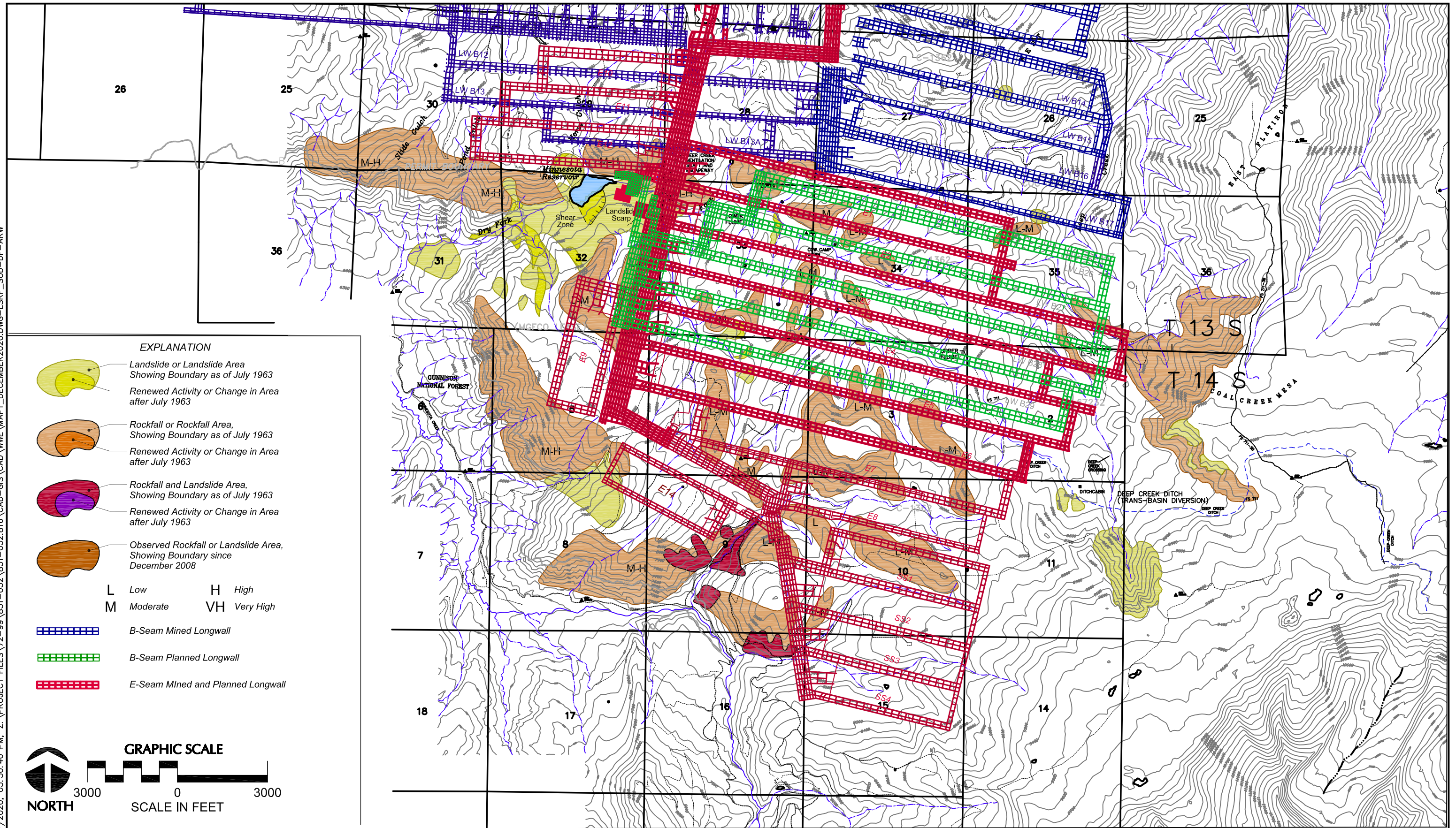


**Figure 11.** Subsidence development curves relative to a point (P) from the 5NW longwall panel at the West Elk Mine (squares), and Somerset room-and-pillar (circles, subsidence more than 90 percent complete and triangles, subsidence only 60 percent complete) as compared to the average National Coal Board curve (1975). This relationship is shown as the ratio of subsidence to maximum subsidence ( $S/S_m$ ) versus the ratio of face position to overburden depth ( $X/d$ ).

## MAPS



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WRIGHT WATER ENGINEERS, INC.  
2490 W. 26TH AVE. SUITE 100A  
DENVER, CO 80211  
(303)480-1700

DESIGN — AWP  
DETAIL — TMV  
CHECK — JMK  
DATE 12/16/18  
SCALE 1"=3000'

**MOUNTAIN COAL COMPANY WEST ELK MINE**  
**LANDSLIDES AND ROCKFALLS IN THE SOUTHERN PANELS, APACHE**  
**ROCKS WEST, AND SUNSET TRAIL MINING AREAS**

PROJECT NO.  
831-032.816

MAP  
1



## **APPENDICES**

## **TECHNICAL MEMO**

### **WEST ELK MINE**

#### **POTENTIAL FOR SURFACE SUBSIDENCE DUE TO DEVELOPMENT MINING AT WEST ELK MINE UNDER PERENNIAL STREAMS**

By Bob Munz, Mine Engineer

December 2020

### **INTRODUCTION**

The purpose of this Technical Memo was to research and summarize the published engineering and scientific literature regarding the potential for surface subsidence due to development mining under perennial streams. The minimum depth of cover required for development mining in the West Elk Mine was then assessed to avoid the potential for surface subsidence should a roof fall/collapse occur.

### **GENERAL DATA**

Development mining produces entries or roadways underground within the mine with a nominal roadway height of 11 feet. Roadway widths range between 18 and 20 feet and the maximum entry-crosscut intersection diagonal spans 34 feet.

Based on drill hole data, the overburden typically consists of 25 to 50 feet of alluvium/colluvium and/or weathered rock near the surface, although alluvium may not be present in some areas. Below this, a variable lithology of sandstones, siltstones, mudstones and shales exist.

### **DISCUSSION**

To ascertain the likelihood that surface subsidence will occur due to development mining, two mechanisms were addressed. One was that a roof fall occurs which would extend directly up to the surface. The second was the potential associated extension of the roof fall resulting in a subsidence basin on the surface.

With competent strata typically present in the immediate mine roof up to at least a height of between 30 and 40 feet, it was assessed that it is practically impossible for a roof fall in an underground roadway or intersection to extend up to the surface and cause subsidence. In a roof fall, the strata tends to form a natural arch (often termed a "failure arch") until it reaches a rock unit that is competent enough to span and in effect "cap" the arch.

Ignoring all other factors such as the presence of anomalously weak or strong strata, general experience suggests that roof falls typically extend up to a height of between 0.8 to 1 times the roadway width or diagonal span of an intersection, as such it was evident that a roof fall should not progress higher than 20 to 34 feet.

In those areas where shallow cover and weak strata or unconsolidated alluvium/colluvium are present, it was determined that in areas that are deeper than approximately 100 feet, the potential for a surface subsidence basin to develop due to development mining is practically impossible. The possibility of a subsidence basin developing as a result of a roof fall and a subsequent progressive “chimney-type” failure, where the roof has no spanning ability, was investigated by Whittaker and Reddish (1989).

The model, shown in Figure 1, indicates that the maximum height of a potential collapse is based on a volume balance between the in situ rock and the caved/bulked material in the “chimney”. Considering the variable roof lithology observed at the mine, it was assumed that the natural angle of repose of the caved roof rock materials will be around 35 degrees and the bulking factor will vary between 1.33 and 1.5. To be conservative, 1.33 was assumed for this assessment (see Wittaker and Reddish (1989) and Canbulet *et al*, 2002).

## CONCLUSIONS

Using the conservatively assumed material properties and development roadway dimensions, the maximum height that a chimney-type failure can progress in a development mining section would range between 50 and 60 feet (see Appendix A for detailed calculations). Further to this point, it is worth noting that the Wardell Guidelines (1975) state that “...in general terms, collapse above a height of  $5t$  (where  $t$  is the thickness of the extracted seam) is unusual, although possible. Collapse above a height of  $10t$  would be quite exceptional”. In this case, that would equate to a roof fall height of between 55 and 110 feet respectively.

Given that drillhole information indicates that the upper 25 to 50 feet of overburden consists of alluvium and weathered rock, for the purpose of this assessment it was assumed that the upper 50 feet of overburden is weak and saturated in the area of perennial streams. As such, this 50 foot depth was added to the above-calculated maximum “chimney-type” failure height (i.e. of 50 to 60 feet) to ensure that the cave does not extend into this zone, potentially allowing the bulked material in the “chimney” to be washed away resulting in subsidence at depths greater than the calculated failure height.

Considering the above, this assessment concludes that the potential for a subsidence basin to develop above a development mining area, located under a perennial stream, is practically impossible at depths greater than 110 feet. Therefore, no future development mining will be conducted at overburden depths shallower than this beneath a perennial stream. It should be emphasized that this assessment used all worst-case conditions and if mining below a perennial stream would be required at

depths less than this, a more in-depth review of the individual area should be completed on a site-specific basis to determine the appropriate minimum depth.

## REFERENCES

Whittaker, B.N. and Reddish, D.J (1989). **Subsidence: Occurrence, Prediction and Control**. Development in Geotechnical Engineering Series, 56, Elsevier Science Publishing.

Canbulat, I., van der Merwe, J.N., van Zyl, M., Wilkinson, A., Daehnke, A. and Ryder, J. (2002). **The Development of Techniques to Predict and Manage the Impact of Surface Subsidence**. CSIR Division of Mining Technology Report No. 2002-0318 for Coaltech 2020.

Wardell, K. and Partners (1975). **Mining Under Tidal Waters**. Report presented to the Ministry for Mines and Power, NSW.

## **APPENDIX A**

### **Height of collapse-chimney equation (Whittaker and Reddish,1989)**

$$z = \frac{4}{(k-1)(\Pi)(d^2)} (2(w)(h^2) \cot(\phi) + h(w^2))$$

k = bulking factor

z = height of collapse-chimney

d = diameter of collapse-chimney

w = width of mined roadway

h = height of mined roadway

$\phi$  = angle of repose of caved rock

#### **Variables for an 18 feet wide roadway:**

k = 1.33

z = variable solved for

d = 7.8m

w = 5.5m

h = 3.35m

$\phi = 35^\circ$

#### **Variables for a 34 feet diagonal intersection:**

k = 1.33

z = variable solved for

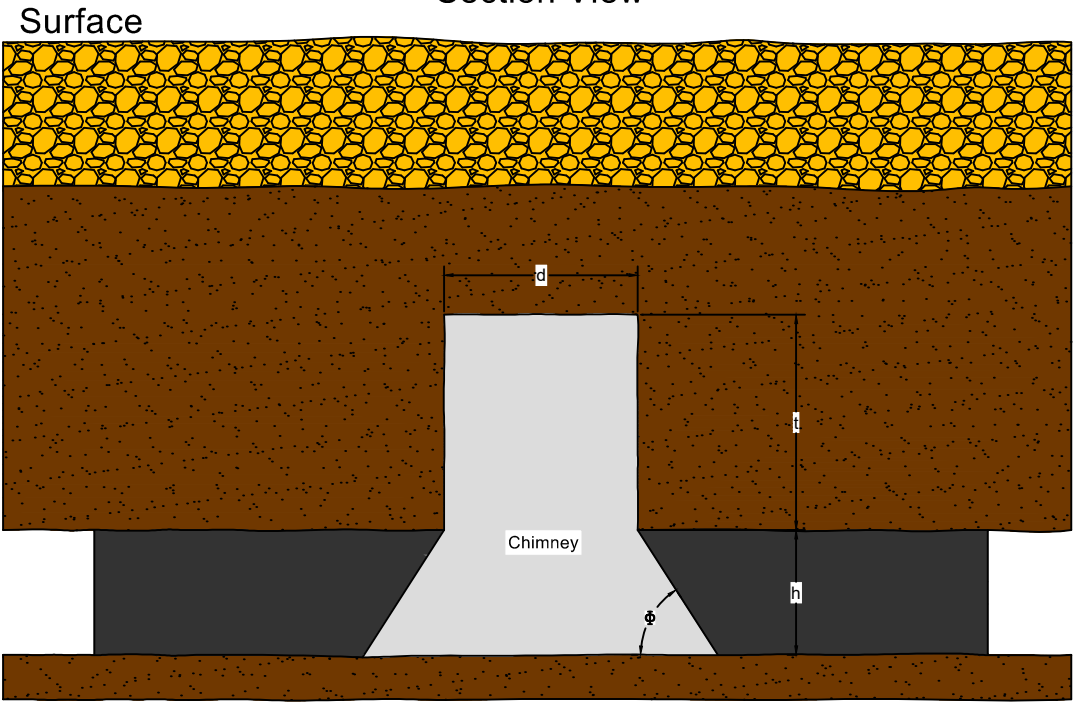
d = 10.3m

w = 7.3m

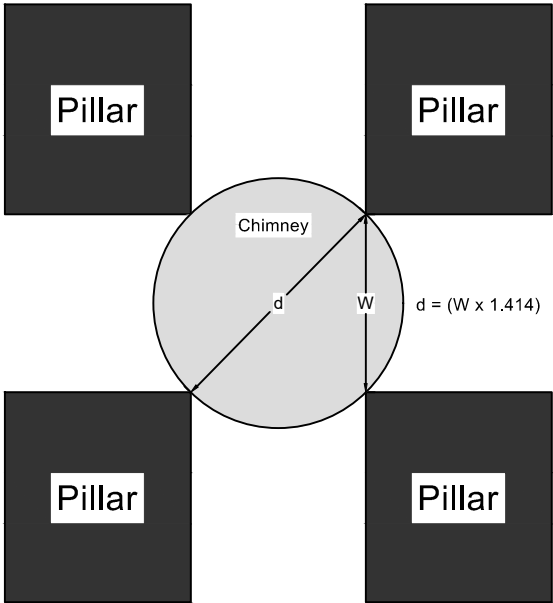
h = 3.35m

$\phi = 35^\circ$

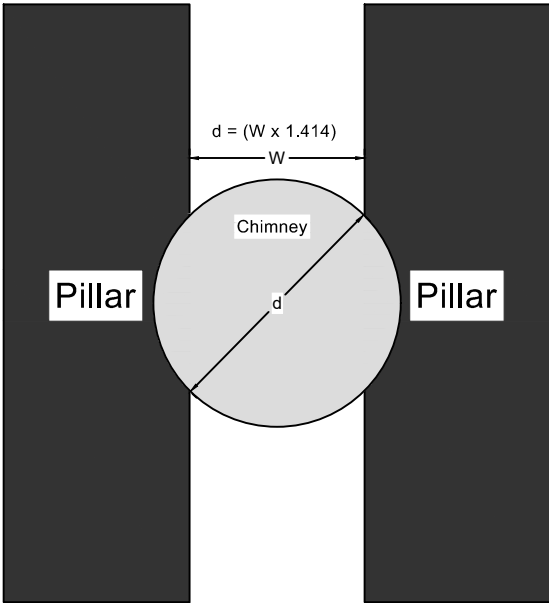
Section View



Plan View (Intersection)



Plan View (Entry)



Height of chimney (z) =  $\frac{4}{(k - 1) (\Pi)(d^2)}$  [2(w)(h<sup>2</sup>) cot Ø + h(w<sup>2</sup>)]

where:

- h = mining height (m)
- Φ = Angle of Repose of the caved rock
- k = Bulking Factor
- w = roadway width(m)

DRAWN	
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12/7/20	GBG
REVISED	
DATE	BY

**ARCH**  
WEST ELK

5174 Highway 133  
Somerset, CO 81434  
Operated by Mountain Coal Company, L.L.C.  
A subsidiary of Arch Resources, Inc.

Figure 1  
Mechanism of Chimney  
Development above an  
Intersection and Roadway in a  
Development Mining Section  
(Whitaker and Reddish, 1989)

0SCALENTS  
feet

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