Appendix C

Subsidence

Draft Environmental Impact Statement/Subsidence

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1.0 INTRODUCTION

Estimated subsidence magnitudes presented in this Draft Environmental Impact Statement for the Red Cliff Mine, Project Area containing the Coal Lease Application and the Existing Coal Lease areas are planned for principally longwall mining of coal north of Mack and Loma Colorado and the south facing Book Cliffs and east of Colorado State Highway 139 as indicated on the general location map titled Red Cliff Mine, Proposed Mine Facilities and Rail Spur. The Coal Lease Application area is east of the Existing Coal Lease that includes the active McClane Canyon Mine and the closed and reclaimed Munger Mine.

2.0 DEFINITION OF TERMS AND SYMBOLS

Terms used to evaluate and analyze subsidence processes and amounts are described below.

Longwall Mining: See Affected Environment/Subsidence for an overview of underground coal mining.

Mining Panel: A rectangular mining area where mine openings are developed and coal is extracted. In longwall mining panels, development entries, or gate roads, are driven at either side of the panel boundaries and the intervening coal is extracted with a longwall cutting machine.

Headgate: Entries and crosscuts driven on the side of the mining panel adjacent to unmined coal, and on the side of the panel that is in the direction of further panel development and used for removal by belt of coal as cut from the longwall face and bringing ventilation to the longwall face.

Tailgate: Entries and crosscuts driven on the opposite side of the mining panel from the head gate entries and provide a path for return ventilation air from the face.

Panel Length and Width (W, L): The length and width of the longwall panel where coal is being extracted.

Subsidence: The vertical downward movement of the overburden and ground surface caused by extracting the coal.

Maximum Subsidence: The maximum vertical downward movement of the overburden and ground surface above the center of the panel caused by extracting the coal.

Tilt and Maximum Tilt (M): The inclination of the ground surface caused by mining the coal in a longwall panel, the vertical displacement difference between two points on the ground surface divided by the horizontal distance between these points; maximum tilt is the maximum inclination that develops as the ground surface deflects downward towards the center of a panel, i.e. the subsidence trough.

Maximum Strain (+E, -E): Strain is the change in length between two points of measurement divided by the original distance between these two points (unit change in length); tensile strain (+e) is the unit elongation between any two points on the surface moving further apart (unit elongation) as the ground surface deflects downward towards the center of a panel; compressive strain (-e) is the unit shortening between any two points on the surface moving closer together as the ground surface deflects downward towards the center of a panel. The maximum values are for the unique conditions present at an individual panel.

Subsidence Trough: A trough-like depression (downwarped area) that occurs directly above and somewhat outside the panel where coal is being extracted; the trough is caused by differential vertical displacement of the ground surface.

Coal Extraction Thickness (m): The thickness of coal being mined; this value may be less than the actual seam thickness, because some coal of low quality may not be mined, some coal may be left in the roof ("top coal") for roof stability, or the seam may be too thick to be mined completely.

Overburden Depth (d): The vertical distance between the top of the coal seam being mined and the ground surface above it.

Critical Panel Width: The minimum mining panel width necessary to cause maximum subsidence on the ground surface, generally along a line over the center of a panel. The length of the mining panel must also be equal to, or exceed this critical width. Critical width varies from 1.0 to 1.4 times the mining depth (overburden thickness).

Critical Panel Length: The length of the mining panel (length of coal area extracted) necessary to cause maximum vertical displacement (1.0 to 1.4 times the overburden depth).

Supercritical Panel Length and Width: A mining panel with a length and width that is greater than the critical mining width.

Super Panel: Two or more mining panels that behave like one large panel because the gateroad pillars have crushed; the overlying subsidence profile looks roughly like a very wide single panel.

Angle of Draw (α): The angle (from a vertical reference) of a straight line projected from the edge of the mining panel to the limit of measurable subsidence outside the edge of a panel at the ground surface.

Break Angle (β): The angle (from a vertical reference) between a straight line projected vertically upward from the edge of the mining panel to the point of maximum extension (maximum tensile strain - +E) at the surface above the panel.

Bedrock: Rock that was originally formed under natural conditions, in contrast to unconsolidated material (colluvium, alluvium, and soil) derived from bedrock.

Cleat: A system of planar cross-bedding fractures in coal; there commonly are two cleat sets that are nearly perpendicular to each other.

Lineament: A linear topographic feature, which can be observed on-site and on aerial photographs, that often indicates a fault or an extensive fracture or fracture system that may more readily erode, frequently controlling the drainage pattern.

Joint: A fracture surface or parting in rock, usually sub-planar, without displacement and frequently one of closely spaced sub-parallel fractures forming a joint set.

Fault: A fracture surface, parting, or series of partings in rock, more extensive than joints, where rock on either side of the surface, or surfaces, is displaced (offset).

Percent Swell: The percent increase in volume of intact rock when broken, collapsed or caved into the open space produced by mining.

Coal Bump: The sudden release of strain energy that may produce an explosion-like sound and shock waves in locations where stress (pressure) on the coal exceeds its strength. May be accompanied by sudden sloughing from the face of an advancing entry, sudden uplift of floor coal and/or sudden outward movement of coal from a rib. More frequently occurs in room-and-pillar mining during pillar robbing during retreat from a panel, when mining the pillars were stressed by load transfer from the entries and crosscuts driven on the advance into a panel.

Rock Burst: The sudden release of strain energy that produces an explosion-like sound, seismic shock waves recorded on seismographs. Rock bursts or coal will generally be violently ejected from ribs, roof and/or floor of mine openings. Generally occurs at depths exceeding 1,500 feet, in stronger rock types and coal seams and in locations where mining has increased pillar and/or rib stress concentrations that exceed the strength of the rock or coal.

3.0 GENERAL MINING INFORMATION

Longwall and room-and-pillar mining are planned for the Red Cliff Mine, with longwall mining predominant. The Proposed Coal Lease tract is bounded by the dashed red line on **Figure 1. *Red Cliff Mine Project and Coal Lease Areas***. There has not been any previous mining in the Coal Lease Application area or the Project Area. The following design specifications were developed for the purposes of describing the potential impacts. A final mine plan will be developed and approved by OSM and the Colorado DRMS. Pillar widths and panel design may vary from those described in this section.

3.1 Panel Design

Panels in the Red Cliff Coal Lease Application are projected to be arranged in groups of three or four, with the long axis of the panels oriented in a north-south direction, at an angle that will range from roughly 20^o to 70^o counterclockwise from the Big Salt Wash drainage, the major topographic feature in the Project Area. The projected north-south panel orientation will align the east-west longwall face between 70^o and 20^o to this major lineament direction. Big Salt Wash and the upper reaches of Buniger Canyon, Hatchet Canyon and Garvey Canyon are between 20^o and nearly 90^o to the direction of the secondary drainages that feed into Big Salt Wash from both sides (Post Canyon, Lapham Canyon and other unnamed smaller side canyons), and the lower reaches of Buniger Canyon, Hatchet Canyon and Garvey Canyon. This panel orientation should minimize any parallel alignment of both linear drainage features to the direction of the longwall face and, thereby, possible periodic loading of the face supports.

A barrier pillar about 200 feet wide is projected to be left between adjacent panel groups. All panels will be oriented in the north-south direction. The longwall panels are projected to be from 800 to 1200 feet wide, and could range from 7,300 feet to 13,500 feet in length. The Main Cameo Seam, also called the Lower Cameo Seam, outcrops at the mine portals, Section 3, T. 8 S., R. 102 W., 6th P.M., the lower reaches of Big Salt Wash in Sections 12 and 1, T. 8 S., R. 102 W., 6th P.M., the lower reaches of Garvey Canyon in Section 12, the lower reaches of Buniger Canyon in Section 1 of the Coal Lease Application area. Therefore, the overburden depth (depth of cover above the Main Cameo ranges from zero in the extreme southwestern part of the Coal Lease Application to slightly more than 2,000 feet on the extreme eastern part of the proposed lease area. The planned minimum overburden depth for longwall mining is 200 feet in order to minimize 1) the potential for chimney caving to the ground surface, 2) the interception and diversion of ground water through the mine workings, 3) the loss of surface water to the fracture zone overlying completed longwall panels and 4) the potential development of up to 20-inch wide surface fractures along the sides of the panels. The planned coal mining height ranges from 8 to 11 feet. The 11-foot maximum planned mining height was used as a conservative maximum thickness in the subsidence analysis.

3.2 Gateroad Pillar Configuration and Design

The currently planned gateroads will generally follow the example on **Figure 2. *Plan View of Three Adjacent Longwall Panels***, where the gateroad pillars involve one row of yield pillars and one row of rigid pillars. The advantage of this design is that it should minimize stress levels at the headgate and tailgate ends of the longwall face. The centerline distance between the planned 20-foot wide gateroad entries will be 100 feet for the projected 80-foot wide rigid pillars. The centerline distance between the 20-foot wide gateroad crosscuts will be 200 feet for the 180-foot long rigid pillars. The centerline distance between the gateroad entries adjacent the 30-foot wide yield pillars will be 50 feet and 100 feet between the crosscuts adjacent to the 80-foot long yield pillars. Every other crosscut for the yield pillars will line up with a rigid pillar crosscut.

Figure 3. *Estimated Gateroad Pillar Loads From Mining First Adjacent Panel* indicates the estimated minimum load and average stress that must be supported by the 30-foot wide by 80-foot long yield pillars, if the yield pillar is not to potentially crush. Figure 3 also indicates the estimated rigid pillar load that must be supported by the planned 80-foot wide rigid pillars, after the longwall face of the first adjacent panel has been advanced roughly one Load Transfer Distance, approximately 329 feet, past any location. The Load Transfer Distance is how far from active mining that deformation or loading in response is measurable or otherwise detectable, and shown on **Figure 4. *Load Transfer Distance Data*** (compiled by Abel, 1988).

Figure 5. *Estimated Gateroad Pillar Loads From Mining Second Adjacent Panel* indicates the estimated minimum load and average stress that must be supported by the planned 80-foot wide by 180-foot long rigid pillars, if the rigid pillar is not to potentially crush, after the longwall face of the second adjacent panel has been advanced roughly one Load Transfer Distance past any gateroad location. It is not essential that the central gateroad entry remain open for ventilation through the gob to the bleeder entries. Two of the active panel tailgate entries will be open to the bleeder entries at all times during mining of the panel. See Figure 2.

The disadvantage of a line of rigid gateroad pillars through the gob is the potential for higher horizontal tensile strain at the ground surface overlying the gateroad because the overburden initially bends toward the first adjacent panel as it is mined and then in the opposite direction when the second adjacent panel is mined, i.e. the tensile strains are additive over rigid gateroads. The optimum situation is for the 80-foot wide rigid pillar to be only temporarily rigid as the second longwall face passes. The rigid pillar can safely be allowed to yield and then crush after it is roughly 100 feet out from the longwall face between collapsed gob on both sides. This, in effect, reduces the tensile strain, and fracture opening, that is directly proportional to the differential vertical subsidence between the gateroad and the maximum subsidence (S_{max}) over the center of the adjacent panels.

3.3 Previous Mining

There is no known previous mining within the proposed coal lease. However, the McClane Canyon Mine is operating in the immediately adjacent existing coal lease on most of Sections 15, 16, 21 and 22, T. 7 S., R. 102 W., 6 P.M. A small coal operation, the Munger Mine now closed and reclaimed, operated in adjacent Section 27. **Figure 1**. ***Red Cliff Mine Project and Coal Lease Areas*** shows the location of these workings.

The McClane Canyon Mine map, **Figure 6**. ***McClane Canyon Mine Workings,*** indicates room- and-pillar advance mining, without pillar robbing on the retreat, to overburden depths just over 1,500 feet (generally 80 by 80-foot pillars on 100-foot centers for 36% recovery). Pillars were robbed on the retreat from other panels at depths of very nearly 1,300 feet. Total coal extraction (recovery) appears to have been as much as 78% within two small (roughly 520-foot maximum width) irregular shaped panels that were retreat mined to depths of 1,100 feet. The mine map indicates that robbing the 100 by 70-foot advance pillars using a method called “christmas treeing” was incomplete and erratic, with many 100 by 70-foot advance pillars and occasional 100 by 30-foot stump pillars left within the panels. This method is no longer permitted by MSHA because of safety concerns. In general, however, panel recovery was approximately 64% when robbing pillars on the retreat, apparently leaving different shaped stump pillars when retreating from different panels. The width of those panels ranged from 350 to 570 feet.

No observations have been reported of surface subsidence effects over the McClane Canyon Mine. Estimates of maximum subsidence (S_{max}), tensile and compressive strains and maximum slope changes were made over the five selected panels and are indicated by number on **Figure 7. *Subsidence Predicted for Five Selected Panels, McClane Canyon Mine*.** The method used combined the British National Coal Board (NCB, 1975) method for longwall subsidence prediction and the room-and-pillar adaptation by Abel and Lee (1984) presented on **Figure 8. *Subsidence Over Room-And-Pillar Workings After Failure***. **Table 1. *Predicted Maximum Subsidence For Selected Panels, McClane Canyon Mine*** presents the estimated super-critical subsidence over each of the selected room-and-pillar panels and the predicted NCB corrected subsidence for the panel width with respect to depth. The predicted maximum surface subsidence for the five panels ranged from 1.52 feet to 2.56 feet. **Table 2. *Predicted Maximum Strains and Tilt for Selected Panels, McClane Canyon Mine*** presents the maximum tensile and compressive strains and slope angle changes In addition, a rough estimate of potential open surface fracture widths was made for each selected panel. This rough estimate was based on the relationship between the vertical subsidence measured over York Canyon Mine longwall panels with known widths and overburden depths, measured surface fracture widths and the NCB predicted maximum surface tensile strains for these known conditions permitted an estimate of the potential width of surface tension fractures.

Table 1. Predicted Maximum Subsidence for Selected Panels, McClane Canyon Mine

Panel Ident.	Panel Width feet (meters)	Panel Mid-Depth feet (m)	Ratio Panel Width/ Depth	L_{max}	Robbed Pillar Width (feet)	L_{max} (Pillar Ht /Panel Depth)	Super-Critical Subsidence (feet)	Panel Correction Factor	Predicted S_{max} feet
1	465 (142m)	900 (274m)	0.517	19.15	20	9.576	35.5% (3.55)	0.55	1.95
2	570 (174m)	400 (122m)	1.425	9.89	25	3.954	24.9% (2.49)	0.61	1.52
3	535 (163m)	500 (152m)	1.070	11.97	30	3.990	25.0% (2.50)	0.81	2.02
4	515 (157m)	800 (2.44m)	0.644	27.86	20	13.93	39.9% (3.99)	0.64	2.56
5	340 (104m)	355 (108m)	0.958	7.77	34	2.285	18.4% (1.84)	0.85	1.56

NOTES: Assumed 160 PCF overburden density, 10-foot mining height, stump pillar widths are minimums after pillar robbing on the retreat from the panel, all values approximate?

Table 2. Predicted Maximum Strains and Tilt for Selected Panels, McClane Canyon Mine

Panel Ident.	Panel Width/ Depth Ratio	Smax/ Depth με	Tensile Strain (+E) Multiplier	Maximum Tensile Strain με open crack (in)	Compressive Strain (-E) Multiplier	Maximum Compressive Strain με	Slope Multiplier (G)	Maximum Subsidence Induced Slope Angle Change
1	0.517	2167	0.82	1780 (1.02)	1.28	2774	3.33	0.72% 0.41° 24.8 min
2	1.425	3800	0.65	2470 (1.50)	0.51	1938	2.75	1.04% 0.60° 35.9 min
3	1.070	4050	0.65	2630 (1.61)	0.55	2228	2.77	1.12% 0.64° 38.6 min
4	0.644	3196	0.57	1830 (1.06)	0.94	3003	3.00	0.96% 0.55° 33.0 min
5	0.958	4393	0.65	2860 (1.77)	0.56	2460	2.78	1.22% 0.70° 42.0 min

The magnitude of the maximum predicted surface extension strains presented in Table 2 would develop roughly over the perimeters of the selected retreat mined panels, which ranged from 1780 $\mu\varepsilon$ to 2860 $\mu\varepsilon$. Extension strains in the predicted range from approximately 1800 $\mu\varepsilon$ to 2900 $\mu\varepsilon$ on the surface would cause repairable damage, ranging from cracking of single story brick walls to cracking of reinforced concrete frames. The predicted tensile strains would result in estimated 1-inch to 2-inch wide tensile cracks at the ground surface. The predicted magnitude of the maximum surface compressive strains ranged from 1940 $\mu\varepsilon$ to 3000 $\mu\varepsilon$, as presented in Table 2 should have developed over the centers of the selected retreat mined panels. Compressive strains in the predicted range would cause repairable damage to structures on the surface.

The predicted maximum increase in surface slope resulting from subsidence over and adjacent to the five selected room-and-pillar panels, presented in Table 2, range from 0.72% (0.41^{o} or 25 min) to 1.22% (0.70^{o} or 42 min). Slope changes of this magnitude could adversely affect floor drainage, turbo generators and overhead crane rail operations. Railroad switching Including all facilities, that depend on rolling of rail cars could be adversely affected. Rubber-tired vehicles could be induced to roll at the grades above 1%. None of the potential structures or land uses indicated was or is present over the McClane Canyon Mine. Increasing a short section of an already steep slope by 0.4^{o} to 0.7^{o} could induce downslope movement. However, the direction that a panel was mined and/or the pillars failed could also flatten a slope. Figure 9. Localized Mining Induced Slope Angle Changes indicates the normally minor effect of the direction of mining on a much steeper slope angle.

3.4 Multiple Seam Mining

Longwall mining is planned as the principal mining method in the Main Cameo Seam. There are no plans to mine any other coal seams, because of the thickness and coal quality of adjacent seams and because of the local 20 to 25-foot thickness where the Cameo Seams split and/or merge.

3.5 Compression Arches and Load Transfer

Compression arches commonly develop across longwall panels where the coal has been and/or is being mined, provided the panel is narrow enough and(or) deep enough for both ends of the arch to span the panel width and bear on rock. These arches are zones of tangential compressive stress where some of the weight of the overburden overlying the arch can be transferred onto abutments; ahead, behind and on either side of the longwall panel being mined (somewhat like the way stone-arched bridges transfer their weight and load to the bridge abutments). However, some or all of the downward deflected rock under the arch will bear on the collapsed rock under the arch. If the width of a longwall panel is too wide or too shallow for the arch to span the panel width, a smaller arch will form, with one side of the arch bearing on and compressing the collapsed gob. The balancing arch abutment can be on the solid barrier pillar behind the starter room, on rigid pillars in the gateroads and on the unmined coal ahead of the advancing longwall face. The arch over the longwall face will follow the advancing face. The arch abutment load following the advancing longwall face will progressively consolidate the collapsed roof rock, the gob. If the face stops moving the face arch will shorten in length and can add load the face supports.

- Compression arches in intact rock can typically support relatively high compressive stresses, compared to tensile stresses, because rock is much stronger in compression than in tension. Major abutment zones in a longwall mining operation will develop on (1) the unmined coal ahead of a longwall face, (2) the unmined coal behind the starter room, (3) the caved zone (gob) behind the supports and possibly on (4) rigid gateroad pillars on either side of the longwall panel. If the planned gateroad pillars do not have sufficient strength to support the arch load abutment, they will yield, transferring that arch load abutment onto unmined coal on one side of the panel and onto the gob left behind the previously mined adjacent panel on the other side. See **Figure 2. *Plan View of Three Adjacent Longwall Panels***.

- In a longwall mining operation, the immediate roof rocks behind the face supports collapse into the volume formerly occupied by the extracted coal. The face supports advance following the shearer, as it cuts each slice of coal off the coal face, much of the weight of the overburden arching over the longwall face will be borne by the re-compressed caved material (gob). The load carried by the gob reduces the abutment load and stress on the coal ahead of the face. Abutment loads acting on the coal ahead of the face are smallest when the roof caves immediately behind the longwall face supports. The magnitude of the weight of overburden transferred is reduced when the length between the advancing face abutment and the following gob abutment is shortened.

- Caving of the immediate roof, which is necessary to form an abutment zone on the gob, is partially controlled by the lithology of the immediate roof rocks. Generally, shales, mudstones and some siltstones, cave readily because the are relatively weak, whereas beds of stronger sandstone and limestone frequently cave with difficulty. Thin-bedded rock units, with closely spaced joints tend to cave more readily than thick bedded rock units, with more widely spaced joints, particularly the stronger rock types that tend to temporarily hang up and then periodically collapse, occasionally violently. Coal mine bumps and outbursts from abutment loaded pillars and from a longwall face, which may occur when the abutment pressure exceeds the strength of the coal, are minimized both in number and magnitude where the immediate and near roof rocks consist of shales and claystones, but may occur in greater frequency and magnitude where the immediate and near roof rocks are strong, i.e. sandstones and limestones. The thick Rollins sandstone, and numerous thinner sandstone beds occur in the coal bearing lower sequence of the Mount Garfield Formation (Mesaverde Group) that contains the Cameo Seam in the Coal Lease Application area. The Rollins sandstone occurs over much of the western Colorado coal mining districts and is locally exposed as a prominent buff-colored cliff-forming outcrop in canyon walls. However, weak immediate roof rocks can cause roof control and support problems in the gateroad entries and crosscuts and caving ahead of the face supports between the time the shearer exposes a portion of the immediate roof and the face supports can move forward to provide the necessary roof support. Coal outbursts that may occur at the coal face can release weak roof rocks to collapse onto the face conveyor.

- Ground stresses and mining induced stress concentrations increase with increasing overburden above a coal seam. Room-and-pillar mining becomes significantly more difficult in overburden more than 1,500 to 2,000 feet thick, because the mine roofs and pillars are already more highly stressed, before coal extraction transfers additional overburden stress. Miners can be forced out of an area by roof falls, pillar slabbing, rib sloughing and floor bumps before planned pillar robbing can be completed. The longwall method overcomes some of the room-and-pillar stability problems. There are no highly stressed pillars present that are split during pillar robbing on the retreat from a panel. Abutment stresses are generally lower and more uniform than in coal mined by the room-and-pillar method. There is also a major body of solid confined load carrying coal immediately in front of the longwall face.

- More frequent and larger magnitude bumps and related seismic activity may occur where a large incompletely caved and consolidated gob area develops behind the longwall face supports. The presence of a thick sandstone bed, such as the Rollins sandstone, in the near roof can be progressively cantilevered further out over the gob until the sandstone suddenly breaks. This is particularly troublesome when the longwall face roughly parallels a widely-spaced and persistent joint set. When the shearer undercuts such a joint, the face supports can be subject to a sudden load increase, i.e. a long line of joint blocks can suddenly be released. When a moderately large rigid gateroad pillar is loaded by the abutment arch from mining of the longwall panel on one side, considerable strain energy can be stored in the pillar. The loading of the pillar will be rapidly doubled when the adjacent panel is mined past the pillar on the other side. If the strength of the gateroad pillar is only marginally strong enough to carry the arched load, the stored strain energy can be suddenly released as a rib bump or outburst. It is necessary to achieve a balance between a rigid gateroad pillar when the first panel passes and a pillar that will yield, but not fail until the second panel has been mined well past the location. A barrier pillar can be left between every set of two longwall panels. This practice can waste part of the coal resource. A rigid barrier pillar between adjacent longwall panels can induce higher tensile strains in the overlying ground surface. Rigid barrier pillars are normally designed to isolate panel groups and protect mains and submains and bleeder rooms. Rigid barrier pillars can locally concentrate stresses in closely overlying and underlying coal seams hindering their future mining.

- For a given point of observation on the surface, the compression arch will have dissipated when subsidence and surface strains have ceased. This, however, takes time, potentially years for the differential stresses to decrease to a stable and permanently supportable level. Active measurable surface subsidence will temporarily decrease significantly when the given point is over a gateroad and between 0.5 to 0.7 times the depth horizontally from any adjacent active longwall panel face. If none of the gateroad pillars are rigid to the load applied when the first adjacent panel passes, less subsidence will occur on the surface over the gateroad when the adjacent longwall panel is mined. When the gateroad pillars yield, the excess load they were unable to support will be transferred to the unmined coal in the adjacent panel. The adjacent gob (collapsed immediate roof rock) will be more uniform if all the gateroad pillars yield when the first panel passes. However, when the adjacent panel passes the yielded pillars major overburden loading must be carried by the coal at the tailgate corner of the face, see Figure 2. Keeping the tailgate entry open to ventilate the longwall becomes a serious problem.

4.0 GEOLOGIC FACTORS INFLUENCING SUBSIDENCE

It is extremely difficult to quantify the impact of geology on the extraction of coal and the resulting subsidence of the ground surface. There are some obvious generalities that can be stated with complete confidence, but predicting what will happen and where is fraught with risk. The overall geology of the coal bearing Mesaverde Group is generally known, but the site specific geologic conditions aren't fully understood because it is only possible to see outcrops, the immediate roof and floor and the coal seam and the overburden lithology is changing.

4.1 Structure

The strike and dip of the bedding, the orientation of known faults, the direction of lineaments, the strike and dip of the bedding cross joints and the spacing and direction of the coal cleats (bedding cross joints in the coal seam) are important factors to consider in the design of longwall mining panels. Bedrock in the Proposed Coal Lease area for the Red Cliff Mine dips northeastward at approximately 3 degrees. The relatively flat dip is not expected to noticeably affect the angle of draw from that of flat-lying beds, based on NCB information (NCB, 1975). The relatively flat dip should not affect the panel orientation.

The lineaments in the lease area are the deeply incised canyons indicated on **Table 3. *Slope Geometries Within Project Area***. The perennial stream in Big Salt Wash canyon and the intermittent streams in the side canyons do not follow the normal dendritic (leaf-like) drainage pattern. The drainage pattern, shown on **Figure 1. *Red Cliff Mine Project and Coal Lease Areas,*** roughly follows the orthogonal (right angle) trellis drainage pattern, also shown on the Garvey Canyon Quadrangle topographic map. The dominant Project Area linear feature is Big Salt Wash which enters the Coal Lease Application area bearing approximately N 22^{o} E and continues for about 12,400 feet where it rotates further easterly, bearing approximately N 31^{o} E for about 6,900 feet, then at N 45^{o} E for 6,100 feet, then exits the Coal Lease Application area after bearing N 54^{o} E for 3,600 feet. From the eastern boundary of the Coal Lease Application area to the eastern boundary of the Project Area, Big Salt Wash bears approximately N 69^{o} E for 4,100 feet. The sub-parallel valley lineaments also follow the same directional rotation, from northeast on the west side of the proposed Lease Area, to a much more easterly direction on the east side of the Project Area.

The secondary lineaments, that are side canyons entering Big Salt Wash from the northwest, bear northwest on the west side (lower Buniger Canyon bears roughly N 57^{o} W) and bear more northerly from west to east across the lease area. The easternmost side canyon on the northwest side of Big Salt Wash, Lapham Canyon, bears approximately N 8^{o} W. The less consistent secondary lineaments represented by side canyons entering Big Salt Wash from the southeast starting with Garvey Canyon that bears about S 82^{o} E, past Hatchet Canyon that bears about S 65^{o} E, to the last unnamed southeast side canyon before the Project Area eastern boundary which bears approximately S 57^{o} E. The southeast side canyons seemingly bear less easterly and more southerly toward the east side of the Project Area.

Table 3. Slope Geometries Within Project Area

Quadrangle	Location	Direction Up Slope	Vertical Height (feet)	Horizontal Distance (feet)	Overall Slope Angles & Grade
Howard Canyon	Munger Creek, 8910 feet from Highway 139 East Salt Creek	N 61° W	980	1900	27° (51%)
Garvey Canyon	Garvey Canyon, 2860 feet off Big Salt Wash road	S 58° E	920	1820	27° (51%)
	Garvey Canyon, 5000 feet east of Big Salt Creek	N 78° E	840	1500	29° (55%)
	Garvey Canyon, 10040 feet east of Big Salt Creek	N 00° W	760	1280	31° (60%)
	Buniger Canyon, 2400 feet west of Big Salt Creek	S 47° W	600	1310	25° (47%)
	Buniger Canyon, 13880 feet northwest of Big Salt Creek	N 62° W	440	1160	21° (38%)
	Big Salt Wash, 2880 feet up from Buniger Creek	S 60° E	920	1500	32° (62%)
	Hatchet Canyon, 6890 feet east of Big Salt Creek	N 34° E	400	456	41° (87%)
	Hatchet Canyon, 7170 feet east of Big Salt Creek	S 47° W	290	490	31° (60%)
	Big Salt Wash, 3680 feet up from Hatchet Creek	S 58° E	760	1240	32° (62%)
	Big Salt Wash, 3970 feet up from Hatchet Creek	N 50° W	760	1200	32° (62%)
	Big Salt Wash, side canyon 6690 feet up from Hatchet Creek	N 08° E	680	890	37° (75%)
	Big Salt Wash, 6920 feet up from Hatchet Creek	S 55° E	560	930	31° (60%)
	Big Salt Wash, opposite side from Post Canyon	S 80° E	880	1500	30° (58%)

Table 3. Slope Geometries Within Project Area (Continued)

Quadrangle	Location	Direction Up Slope	Vertical Height (feet)	Horizontal Distance (feet)	Overall Slope Angle & Grade
Garvey Canyon	Post Canyon, 4180 feet northwest from Big Salt Wash	N 78° E	720	1300	29° (55%)
	Post Canyon, 5420 feet northwest from Big Salt Wash	N 30° E	600	860	35° (70%)
	Big Salt Wash, 1080 up side canyon, after 3280 feet up Big Salt Wash from Post Canyon	N 06° E	520	1130	25° (47%)
	Lapham Canyon, 2080 feet from Big Salt Wash	N 68° E	480	740	33° (65%)
	Lapham Canyon, 5550 feet from Big Salt Wash	N 61° W	440	760	30° (58%)

4.2 Lithologic Factors Affecting Subsidence

Different lithologies (rock types) have differing strengths and therefore differing swell potential when broken. As indicated on **Table 4. *Bank Density, Swell Factor and Percent Free Swell for Selected Rocks and Soils,*** there is considerable variation in the percent swell between rock types and within rock types. The height of caving above the mine workings is reduced where the roof rocks consist of strong (high percent swell) sandstones compared to weak (low percent swell) shales, mudstones or soft siltstones. However, the height of rock fracturing above mined openings is greater for strong, brittle sandstones compared to weak, more yieldable shales, mudstones and soft siltstones. The mean percent swell of the overburden rocks controls the potential maximum height of the collapse zone upward in the immediate roof above a longwall panel, an entry or an intersection between an entry and a crosscut. **Figure 10. *Potential Collapse Heights Above Different Mine Opening Geometries*** by Piggott and Eynon (1977) provides a percent swell based method for predicting the maximum collapse height in the rock above different mining geometries, i.e. rectangular collapse over large area panels, wedge collapse over long narrow entries and conical collapse over four-way roadway intersections. The calculation simply is for what height of roof rock must collapse and expand to fill an underlying mined void applying three types of collapse geometry. Once the void and chimney are filled with caved rock (gob), it is assumed that further roof collapse will be prevented by the broken rock fill.

Gray, Bruhn and Turka (1977) tabulated data on 126 chimney collapses above room-and-pillar workings in the nominally 6-foot thick Pittsburgh Seam to the overlying ground surface. The relative cumulative frequency curve, **Figure 11. *Cumulative Percent of Chimney Collapse Height,*** suggests that there is a very small probability, 0.8 percent, that a collapse chimney of any type will progress upward through 200 feet of Pennsylvanian formation coal overburden to the ground surface, irrespective either mining geometry or collapse geometry. Gray et al. (1977) recorded the elapsed time after mining that chimneys, sinkholes, breached the ground surface and pillar collapse troughs dropped the ground surface, shown on **Figure 12. *Time Interval Between Mining and Surface Breached or Dropped***. They indicate that the time interval can be as much as 100 years. The McClane Canyon Mine has extracted approximately 36% of Cameo Seam coal by advance room-and-pillar mining at approximately 225 feet of depth, apparently without any chimney collapse to the overlying ground surface. This can be seen on **Figure 6**. ***McClane Canyon Mine Workings***. This is common practice for operating coal mines because the roof is reinforced as it is exposed and can be re-supported as required during the operating life of the mine to prevent progressive chimney collapse. After a mine is closed progressive deterioration of the roof can result in chimney failures, which at shallow depths can and frequently do breach the ground surface. Areas where the overburden thickness is less than 200 feet above the Cameo Seam in the Proposed Coal Lease area should be considered at risk for long-term chimney collapse to the surface. The 200-foot overburden contour is shown on **Figure 13. *Overburden and Outcrop Map for the Project Area***. The 200-foot overburden contour extends approximately 360 feet upstream from the outcrop line in Big Salt Wash and approximately 550 feet upstream from the outcrop line in Garvey Canyon. Long-term protection from chimney subsidence to the overlying ground surface can be provided in such shallow overburden by partially backfilling the entries in these two areas upon final closure of the Red Cliff Mine.

Table 4. Bank Density, Swell Factor and Percent Free Swell for Selected Rocks and Soils

Sedimentary Rocks or Soils	Bank Density	Swell Factor	Free Swell
Clay, natural	126 PCF	0.82	22%
Coal, anthracite	100 PCF	0.74	35%
bituminous	80 PCF	0.74	35%
Conglomerate	153 PCF	0.72-0.63	40-60%
Earth, wet	126 PCF	0.79	27%
loam	96 PCF	0.81	23%
Gravel, pit run	135 PCF	0.89	12%
Limestone	155-163 PCF	0.57-0.60	67-75%
typical values		0.59	69%
Montmorillonite, chlorite, kaolin illite, smektite	141 PCF	0.77	30%
Sand, dry	100 PCF	0.89	12%
damp	120 PCF	0.89	12%
wet	130 PCF	0.89	12%
Sandstone	153-157 PCF	0.60	67%
Shale, mudstone	104 PCF	0.75	33%
Siltstone, hard	153-157 PCF	0.57-0.60	67-75%
soft	126 PCF	0.82	22%

Free swell (%) = change in volume broken as a percent of original bank volume
Swell factor = broken density/bank density

Adapted from: Caterpillar, Inc., 1987, Caterpillar performance handbook, p 740 and Euclid Road Machinery Co., 1953, Estimating production and costs

4.3 Lithology and Angle of Draw

The purpose of the reasonably nearby drilling through the Mount Garfield formation for Dorchester Coal Company's Fruita Project was to explore for potential mining of the Main Cameo which ranged from 10 to 29 feet thick at depths of up to 1600 feet in their proposed lease area. The reported lithologic distribution of rock types above the Main Cameo from 19 drillholes, which individually penetrated between 67 and 1316 feet of overlying rock, for a total of 13,880 feet of drilling is presented in **Table 5. *Lithologic Distributions for Dorchester Project Overburden***. The overall average percentage of sandstone in the overburden is approximately 46%. Abel and Lee (1984) collected data on the relationship between measured angles of draw and the lithologic distribution in the overburden above several coal seams. **Figure 14. *Estimated Angle of Draw in Relation to Percent Sandstone and Limestone*** presents the relationship. The Dorchester Project drilling indicated 46% sandstone and no limestone and predicts a 19^{o} angle of draw (α). The Dorchester drilling indicated considerable lateral rock type variation. Therefore, it should be anticipated that there will be a similar variation in the angle of draw. The range of sandstone percentage as determined from the drillholes was from 28 to 65%, suggesting a range for the angle of draw from just over 15^{o} to over 25^{o}. Angles of draw were predicted at 25^{o} at two coal mines in Colorado mining in the Mesaverde Group based on drillhole lithology. Later survey measurements indicated angles of draw of 21^{o} and 22^{o}.

A 19^{o} to 22^{o} angle of draw is on the low end of the range of values reported for the countries listed on **Table 6**. ***Angles of Draw for Coal Mining in the United States and Europe*****.** The British National Coal Board's (NCB) conservative 35^{o} angle of draw has, however, been measured in Pennsylvania (Auchmuty, 1931). The larger NCB angle of draw estimate will be used because it should overestimate the area outside a longwall panel potentially affected by mining. In addition, the NCB maximum subsidence value (S_{max}) calculated from the flatter English terrain measurements was 17% to 21% greater than what was measured for ridge tops over three longwall panels in Mesaverde Group rocks and mountainous terrain at the York Canyon Mine west of Raton, New Mexico. NCB predicted subsidence in topographic lows were 55% greater than measured at the York Canyon Mine. This implies that the maximum tensile strain, compressive strain and tilt estimated using the NCB method may be similarly greater than what will be measured in the Project Area because the strains and tilt are directly proportional to the maximum panel subsidence (S_{max}) value.

5.0 TOPOGRAPHIC FACTORS AFFECTING SUBSIDENCE

5.1 Rugged Terrain

The Red Cliff Mine Project Area is located in canyon-ridge topography. As shown on Table 3, overall slope angles range from 21^{o} to 41^{o} (38% to 87%) for canyon walls ranging from 400 feet to 920 feet high. Cliff sections are present on some canyon walls where thicker sandstones outcrop. Because of this rugged terrain, subsidence related surface impacts may change several times as the overburden depth changes along the roughly 7,300-foot to 13,500-foot lengths of the longwall panels. Subsidence, strain and tilt predictions will be less certain than would be the case in more gentle and flatter terrain. For example, vertical displacement may be as much as 30 percent greater over narrow ridge tops. The overburden ahead of a moving longwall face will move down slope as the subsidence trough ahead of the longwall face approaches but will not be

Table 5. Lithologic Distributions for Dorchester Project Overburden

Drillhole	Above Main Cameo (feet)				Total	Percent
Number	Coal	Sandstone	Siltstone	Shale/Mudstone	(feet)	Argillaceous
1	6 (1.2%)	254 (50.0%)	66 (13.0%)	182 (35.8%)	508	48.8%
2	6 (0.6%)	375 (37.7%)	451 (45.3%)	163 (16.4%)	995	61.7%
4	17 (5.8%)	150 (51.0%)	26 (8.8%)	101 (34.4%)	294	43.2%
11	12 (0.9%)	647 (51.0%)	320 (25.2%)	290 (22.9%)	1269	48.1%
16	21 (2.1%)	453 (44.2%)	97 (9.5%)	453 (44.2%)	1024	53.7%
17	9 (0.9%)	486 (46.9%)	55 (5.3%)	487 (47.0%)	1037	52.3%
18	28 (2.5%)	544 (48.1%)	101 (8.9%)	457 (40.4%)	1130	49.3%
30	5 (0.4%)	504 (38.3%)	593 (45.1%)	214 (16.3%)	1316	61.4%
32	15 (2.6%)	255 (44.4%)	130 (22.6%)	174 (30.3%)	574	52.9%
33	20 (2.8%)	197 (27.9%)	280 (39.7%)	209 (29.6%)	706	69.3%
37	15 (1.4%)	563 (51.7%)	226 (20.8%)	284 (26.1%)	1088	46.9%
38	11 (1.0%)	577 (49.9%)	186 (16.1%)	383 (33.1%)	1157	49.2%
39	12 (2.8%)	212 (49.4%)	36 (8.4%)	169 (39.4%)	429	47.8%
42	3 (2.0%)	75 (50.7%)	6 (4.1%)	64 (43.2%)	148	47.3%
CM1	4 (6.0%)	46 (68.7%)	0 (0.0%)	17 (25.4%)	67	25.4%
CM2	13 (4.0%)	150 (46.7%)	51 (15.9%)	107 (33.3%)	321	49.2%
CM3	7 (1.2%)	297 (50.5%)	213 (36.2%)	71 (12.1%)	588	48.3%
CM4	10 (1.0%)	485 (47.6%)	249 (24.5%)	247 (26.9%)	1018	51.4%
CM7	10 (4.7%)	137 (64.9%)	25 (11.8%)	39 (18.5%)	211	30.3%
Total						
Footage	224	6407	3111	4138	13880	
Percentage	1.6%	46.2%	22.4%	29.8%		52.2%

Table 6. Tabulated Angles of Draw for Coal Mining in the United States and Europe

Country or District	Brauner (1973, p. 9)	Wardell (1959, p. 530)	Newhall and Plein (1934, p. 65)	Pendleton (1985)	Collins (1977)
Netherlands-------	35°-45°	35°-45°	---------	--------	--------
Ruhr-----------------	30°-45°	---------	---------	--------	--------
Lower Rhine------	----------	29°-39°	---------	--------	--------
France--------------	35°	---------	---------	--------	--------
Great Britain------	25°-35°	28°-40°	---------	--------	--------
Poland--------------	----------	19°-34°	---------	--------	--------
Pennsylvania-----	20°	---------	20°-25°	--------	--------
South Wales------	----------	---------	---------	--------	32°-40°
Colorado-----------	----------	---------	---------	21°	--------

able to push uphill against gravity after the face passes. If the longwall panel subsequently advances under the ridge, that side of the ridge will displace down slope on that side of the ridge. In the course of extracting the underlying coal, a ridge with steep slopes in adjacent valleys will subside more than would be the case in flat terrain. Parts B and C of **Figure 9. *Localized Mining Induced Slope Angle Changes*** indicates how this will occur. The potentially additive subsidence on ridges will increase the tensile strain and the width of open surface cracking.

Higher compression ridges, but negligible tensile fractures, are likely to occur in narrow valley bottoms, because the overburden on both sides will try to move toward the bottom of the valley as the subsidence trough approaches and then passes the valley bottom. Consequently subsidence impacts are likely to be greater on narrow ridges and lesser in narrow valley bottoms than they would be in more subdued terrain.

- Strains and displacements on steep slopes with thin alluvial cover, particularly cliffs, may cause surface fractures on the order of a several inches to more than two feet wide and possibly 25 feet deep, compared to a fraction of an inch to a few inches wide and a few feet deep in valley bottoms at the same overburden depth. When the relief is subdued and terrain gentle, the surface fractures will be consistent in width and depth and generally follow a smoothed ovaloid around the panel perimeter. See **Figure 4. *Plan View of Typical Subsidence Over a Longwall Panel*** in Affected Environment/Subsidence. Cracks will tend to be widest (approaching 20 inches wide) and deepest (possibly 50 feet) along prominent joints and fractures on the steepest slopes and cliffs, which, in turn may become less stable and more susceptible to landslides and rockfalls.

- Landslides and rockfalls will be most likely to occur where mining approaches the outcrop, and the overburden depth is decreasing. Tilting and tensile strain elongation of the ground surface is greatest where the overburden is the least. The greatest subsidence impact is likely to occur in geologic hazard areas where either of the following two conditions occur:

  1. The subsidence-induced tilt direction, which is towards the longwall panel, parallels the slope direction, which temporarily increases the slope of the valley wall, but the progressively greater depth progressively decreases the surface tensile strain. See **Figure 9. *Localized Mining Induced Slope Angle Changes*** in part C.

  2. The direction of longwall face advance is in the same direction as the slope inclination, which opens progressively wider surface fractures, i.e. as the longwall face moves from deeper towards shallower overburden progressively increases the surface tensile strain, but temporarily decreases the slope of the valley wall. See part B of **Figure 9. *Localized Mining Induced Slope Angle Changes***.

5.2 Variable Overburden Thickness

For any mining panel width and coal extraction thickness, the maximum subsidence, tilt, and strain at the ground surface should decrease with increasing overburden depth. A single panel may range from supercritical under shallow overburden to subcritical under deeper overburden.

- Gate road yield pillars will tend to yield more with increasing overburden depth, such that two or more adjacent panels begin to approach the theoretical behavior of a single super-panel at overburden depths greater than 1,000 to 1,500 feet. At these depths, gateroad yield pillars may be loaded beyond the minimum loading and will begin to crush. Even yield pillars are extremely unlikely to yield to the level of the adjacent caved, broken and compacted gob behind the shield canopies at the face of the longwall panel. **Figure 3 *Estimated Gateroad Pillar Loads From Mining First Adjacent Panel*** indicates the minimum load the planned 30-foot by 80-foot gateroad yield pillar must support. The 80-foot by 180-foot gateroad pillars are designed to support the load arched from over the gob when the first adjacent panel passes as the result of the yielding of the 30-foot by 80-foot pillar. Figure 3 also shows the estimated maximum rigid pillar load transferred onto the 80-foot by 180-foot gateroad pillar after the first adjacent panel has passed.

  The 80-foot by 180-foot gateroad pillar could be allowed to yield after the first adjacent panel has passed. In that case, as the second panel is retreated a major arched load could be transferred onto the tailgate corner of the second adjacent longwall panel from both gob areas shown on Figure 2,. Rigid gateroad pillars, such as the 80-foot by 180-foot pillars, are designed to help protect the tailgate corner during longwall mining.

- Rigid gateroad pillars, such as the 80-foot wide by 180-foot long gateroad pillars, shown on **Figure 5. *Estimated Gateroad Pillar Loads From Mining Second Adjacent Panel***, must support arched loads from over both adjacent panels or they will yield and very likely crush a short distance after the second panel has passed, as indicated by the arrow showing the "Panel Face Retreat Direction" on **Figure 2**. ***Plan View of Planned Gateroad Pillars***. The estimated rigid pillar loading shown on Figure 5 is for 1500 feet, but individual Red Cliff Mine panels may have as much as 2000 feet of overburden in the Coal Lease Application area. At 1500 feet, the maximum estimated rigid pillar load on the 80-foot by 180-foot resulted in an estimated stress of 6930 psi. At the planned maximum depth of 2000 feet, the estimated rigid pillar stress is 10760 psi, approximately a 55% increase. Both rigid pillar stresses exceed the 4760 psi uniaxial compressive strength of specimens from the Cameo "B" Seam at the Roadside Mine near Palisade, Colorado. However, an 80-foot wide by 11-foot high pillar should be stronger than the ASTM Standard 2-inch diameter by 4-inch long core test sample specified by American Society for Testing and Materials (ASTM), in the method for unconfined compressive strength of intact rock core specimens D2938. The rigid pillar has a width/height ratio of 7.3 versus 0.5 for the core specimens. The central part of the rigid pillars will be capable of carrying much greater stresses because of the central core of the pillar is confined by the coal around the core.

  Pillar ribsides of rigid pillars at the Roadside Mine rapidly sloughed into the adjacent entries and crosscuts at 1800 feet of depth. When the coal sloughed off such a pillar ribside was removed, the entry width had increased. The shape on the exposed pillar ribsides is commonly referred to as "hour glassed". After such a cleanup, the pillars sloughed again, and repeated until the pillar ribsides were supported and restrained.

6.0 SUBSIDENCE ESTIMATION OVER CAMEO SEAM LONGWALL PANELS, RED CLIFF MINE PROJECT AREA

The primarily graphical subsidence estimation method developed by the British National Coal Board (NCB, 1975) for estimating trough subsidence over longwalls was used for the Red Cliff Mine Project Area. The method was based on 177 profiles measured over named longwall panels and 10 over unnamed longwall panels. This provides a means of making a worst-case estimate of the maximum vertical subsidence (S_{max}), tensile strain (+E), compressive strain (-E) and slope change or tilt (G) of the ground surface anywhere over a longwall panel, provided the mining height (m), mining depth (h) and panel dimensions are known. Graphs provide a means of constructing a subsidence profile from the center of a longwall panel across the sides or ends of the panel to the limit of subsidence. A graph also provides a method of constructing a horizontal strain profile from the center of a longwall panel across the sides or ends of the panel to the limit of subsidence.

The NCB method has been routinely used to estimate the maximum potential magnitude and location of tensile and compressive strains and slope inclination changes that could be induced at the ground surface by planned longwall mining. Being able to predict worst-case subsidence effects has made it possible to take measures to mitigate damage to surface structures. Coal has been routinely mined under cities, highways, pipelines, power lines, factories, railroads, rivers, bridges, harbors, cathedrals, churches, schools, historic castles and keeps and other sensitive structures. The method provides conservative estimates so that engineering adjustments could be made to accommodate the conservatively predicted (worst case) subsidence effects before they develop. The NCB method has been used to conservatively estimate subsidence impacts in the Project Area.

- The NCB method, which is a step-by-step procedure for predicting subsidence effects from mining a longwall panel based on the fundamental factors of coal extraction thickness, panel width between gateroad pillars and overburden depth. Initially the method provides a graph for estimating the maximum vertical subsidence reduction factor for the mining height based on Panel Width versus Panel Depth (**Figure 8. *NCB Panel Width/Depth Maximum Subsidence (S_{max}) Prediction*** in Affected Environment/Subsidence). Then the method provides a graphical plot of various proportions of the maximum subsidence along a profile based on the Panel Width/depth ratio from the center of a panel, across the side of the panel to the limit of subsidence outside the panel (**Figure 9. *NCB Subsidence Profile Graph*** in Affected Environment/Subsidence). The distance from the center of the panel is in terms of the panel depth. The next graph provides multipliers for the ratio of the maximum subsidence divided by the depth for a wide range of Panel Width/Depth ratios. The values taken from the graphical plot for the particular Panel Width/Depth ratio cross three lines, the "EXTENSION" line estimates the maximum tensile strain (+E), the "COMPRESSION" line the maximum compressive strain (-E) and the "SLOPE" line the maximum slope change or tilt (G), (**Figure 11. *NCB***

Maximum Strain and Slope Prediction Graph in Affected Environment/Subsidence). The final graph provides various proportions of the maximum tensile strain (+E) and maximum compressive strain (-E) along a profiles from the center of a panel, across the side of the panel to the limit of subsidence outside the panel (**Figure 12. *NCB Horizontal Strain Profile Graph*** in Affected Environment/Subsidence**).** The method has been modified by others to extend its application to room-and-pillar panel mining and to consider the impact of varying proportions of sandstone, limestone and shale or mudstone in the overburden.

- The NCB subsidence method is used directly for longwall mines and has been modified for room-and-pillar mines. Reported subsidence predicted and measured over room-and-pillar workings at the Roadside Mine east of Palisade Colorado predicted 1.61 feet, measured 1.02 feet in the Cameo Seam; the Eagle No. 5 Mine southwest of Craig, Colorado reported having measured 10% more subsidence than predicted and the Southland Mine near Canon City, Colorado predicted 1.51 feet, measured 0.89 feet. The NCB method has been applied for subsidence prediction over a longwall panel in the Mid Continent Mine west of Redstone, Colorado predicted 4.99 feet and measured 1.71 feet; the York Canyon Mine west of Raton, New Mexico predicted 8.1 feet and measured 7.09 feet. Subsidence was predicted using a modified NCB method at the Chimney Rock coal augering mine east of Pagosa Springs, Colorado predicted 2.59 feet, measured 0.49 feet.

6.1 Subsidence Zones

There are approximately four overburden zones to consider and analyze in the trough subsidence process over a longwall panel. **Figure 5. *Conceptual Representation of Subsidence Deformation Zones*** in Affected Environment/Subsidence presents one such representation (Peng, 1992). There a four generally agreed zones of overburden response to longwall mining. They are (1) the caved or collapsed zone, (2) the fractured zone, (3) the continuous deformation zone and (4) the near-surface zones. These zones are really transitional from one to another, and not sharply bounded.

6.1.1 Caved Zone

After the removal of the coal under the roof of a longwall panel, the immediate roof collapses and caves upward to fill up the mined void. Piggott and Eynon (1977) calculated the height of the collapse zone over a longwall panel in coal measure rocks as 2 to 3.3 times the mining height based on a typical range of percent swell of 30 to 50%, see **Figure 10. *Potential Collapse Heights Above Different Mine Opening Geometries*.** The collapsed rock is a jumbled mass of rubble that will be partially reconsolidated by the overburden load. The collapsed rock no longer gives the appearance of having been part of a bedded or stratified sedimentary formation. H.F. Schulte (1957) reported that the height of the rubble zone exposed in a winze excavated down into the center of a worked area was 2.4 times the mining height above the seam floor. P. Kenny (1959) reported observing and measuring the active height of caving into the original roof above a longwall panel to range from two to four times the mining height, depending on the angle of repose, fragmentation, bed thickness and swell of the immediate roof rocks. S. Peng (1992) reported the height of the caved zone is normally 2 to 8 times the mining height, depending on the properties of the immediate roof and the overburden. The caved zone is extremely permeable and if the caved zone breaches an aquifer the water will enter the mine workings as an unrestricted flow.

6.1.2 Fractured Zone

Rocks in this zone undergo fracturing and fissurization both completely and partially across one or more rock layers and along bedding surfaces between layers. The bottom of the fracture zone is located where an individual bedding contact can be traced despite offsets and slight rotations between rock blocks. The fracturing decreases upward from open interconnected fractures and bedding surfaces to tight fissurization. Stream flow readings and water level fluctuations indicated by piezometers and packer tests in drill holes before, during and after longwall mining under and within the angle of draw outside panels have been used to determine the approximate upper boundary of the fracture zone (Bauer, et al, 1995: Mattson and Meggars, 1995a; Mattson and Meggars, 1995b; Peng, 1992). Whenever a monitoring well bottoms in what will be part of the fracture zone the water level and(or) pressure will initially rise slightly as the longwall face approaches, then drop significantly shortly after the longwall face passes and finally may recover somewhat over an extended period of time. Bauer, et al. (1995) reported that the water level returned to its pre-mining elevation within 2 years after mining ceased.

Peng (1992, p. 143) indicates that the lower 2/3 of the fracture zone has increased hydraulic conductivity as the result of fracturing associated with subsidence. Peng states that the upper 1/3 of this zone has only minor, unconnected fractures and thus undergoes only a minor increase in water conductivity as the result of being subsided by longwall mining. Booth and Spande (1992) report an order of magnitude increase in water conductivity for an overlying sandstone as the result of subsiding in the fracture zone.

According to Peng (1992, p. 6-8), the height of fracturing is a function of lithology and thickness of the stratigraphic layers. **Table 7. *Formulae for Predicting Fracture Zone Height*** (modified from Peng, 1992, p. 7), predicts the height of the fracture zone based on the competency of the overburden as indicated by the unconfined compression strength. The results of the application of this table to the planned 11-foot mining height at the Red Cliff Mine could result in the fracture zone extending 183 feet or 16.6 mining heights up into the overburden if that overburden were entirely “Hard and strong rock”; to a potential height of 123 feet or 11.2 mining heights if the overburden were “Medium hard rock”; to a potential height of 71.5 feet or 6.5 mining heights if that overburden were entirely “Soft and weak rock” overburden; to a potential height of 44.4 feet or 4 mining heights if that overburden were entirely “Weathered soft and weak rock” overburden.

The Mesaverde Group overburden is a laterally and vertically variable mixture of sandstone, argillaceous shale/mudstone, siltstone and coal. **Table 5. *Lithologic Distributions for Dorchester Project Overburden***, containing the lithologic logs from 13,880 feet of drilling for 19 drill holes at the nearby Dorchester Project site, indicates the probable considerable variability at the Red Cliff Mine Project Area. The probably dominant sandstone lithology, around 46%, could not be considered the “Hard and strong rock” with uniaxial compression strength greater than 5888 psi indicated on Table 7. The fact that it is a cliff former where present in canyon walls suggests it is locally probably in the range for “Medium hard rock”. On the other end of the scale, the “Weathered soft and weak rock” does not fit the overburden, because it is not weathered. Therefore it is recommended that the maximum height of the fracture zone

Table 7. Formulae for Predicting Fracture Zone Height
(modified from Peng, 1992 referencing Liu, 1981)

Rock Type	SI System	English System
Hard and strong rock (Good water conductivity)	$H_f = \frac{100m}{1.2m+2.0}$ meters $\sigma = \pm 8.9$ meters	$H_f = \frac{100m}{0.366m+2.0}$ feet $\sigma = \pm 29.2$ feet
Medium hard rock (Worse water conductivity)	$H_f = \frac{100m}{1.6m+3.6}$ meters $\sigma = \pm 5.6$ meters	$H_f = \frac{100m}{0.488m+3.6}$ feet $\sigma = \pm 18.4$ feet
Soft and weak rock (Bad water conductivity)	$H_f = \frac{100m}{3.1m+5.0}$ meters $\sigma = \pm 4.0$ meters	$H_f = \frac{100m}{0.945m+5.0}$ feet $\sigma = \pm 13.1$ feet
Weathered soft and weak rock (Bad water conductivity)	$H_f = \frac{100m}{5.0m+8.0}$ meters $\sigma = \pm 3.0$ meters	$H_f = \frac{100m}{1.524m+8.0}$ feet $\sigma = \pm 9.8$ feet

1. h_f= fractured zone height, m = mining height, σ = standard deviation. All units in meters (SI System) or feet (English System).

2. Rock type is classified based on the uniaxial compressive strength (c): hard and strong rock c > 5888 psi (39.23 MPa); medium hard rock c = 2644 - 5888 psi (19.62 - 39.23 MPa); soft and weak rock c = 1200 - 2844 psi (8.28 - 19.62 Mpa). (Original in Peng, 1992, p7)

for planning should be a weighted average of 46% “Medium hard rock” and 54% “Soft and weak rock”, for a worst case estimate for the fractured zone height as 95 feet.

0.46 times 123 feet plus 0.54 times 71.5 feet = 95 feet

The potential for draining surface water into the Red Cliff Mine is low, but probably precludes longwall mining under stream courses and water impoundments when the bedrock overburden thickness is less than 95 feet. Consideration should be given to geophysically measuring the thickness of alluvium beneath valley where the total overburden thickness above the Cameo Seam is 200 feet or less, as shown on **Figure 13. *Overburden and Outcrop Map for the Project Area***.

6.1.3 Continuous Deformation Zone

This zone, which is transitional to the underlying fracture zone, is from the upper limit of the fractured zone to the near-surface weathered bedrock and soil zone. See **Figure 5 *Conceptual Representation of Subsidence Deformation Zones*** in Affected Environment/Subsidence. This zone contains subsidence induced fractures, but the fractures in this zone do not persist from bed to bed and generally not across even a single bed. Pre-mining cross bedding joints remain tight through the subsidence induced downward deflection that moves with the underlying and advancing longwall face. Obviously, the continuous deformation zone can have considerable thickness, potentially hundreds of feet thick, when the overburden depth to the mining horizon is a 1,000 feet or more and the fracture zone is on the order of 100 feet.

The downward deflection of the beds during subsidence above the fracture zone as the overburden beds bend toward the void left by the longwall mining operation. The deflecting beds approximate psuedo-elastic plates. The upper part of each plate-like bed undergoes subsidence induced tensile strains which may open bedding cross joints. These tensile strains are in the area from the limit of subsidence outside the panel and the inflection point between downward bending and upward bending slightly inside the active panel from the gateroad pillars. There is a similar inflection point slightly inside the active panel from the starter room. when it bends down toward the void left by the longwall mining operation. The lower part of each plate-like bed undergoes subsidence induced compressive stress that balances the tension. In the part of the trough-like subsidence curve where the bed is bent back to its original inclination the stresses are reversed in each bed, compression in the upper part and tension in the lower part. Strain relief overcoring has demonstrated that there are 3-dimensional compressive stresses in the rock below the ground surface. The horizontal compression appears to prevent the opening of pre-mining cross bedding joints in the tensile stress zone associated with the downward bending in the continuous deformation zone. After the longwall is completed, the bending pattern will be repeated over the recovery room pillars.

6.1.4 Near-Surface Zone

Most subsidence measurements are made at the top, ground, surface of this zone. From top to bottom, the near-surface zone typically consists of:

(a) A relatively thin layer, generally a few feet at most, of either fragmented residual soil, weathered from the underlying rock, or colluvium that has moved down slope under gravity to where it lies on weathered rock, or alluvium that has been transported over the weathered rock by flowing water;

(b) Beneath the fragmented surface material is the weathered, chemically altered, weakened and frequently iron-stained bedrock. The bedding cross joints are frequently slightly-open and soil-filled. There may even be minor breaks along some bedding contacts. The weathered bedrock blocks remain in position with respect to each other, but may be completely detached but in-place blocks of the weakened rock. The tensile strength of a mass of weathered bedrock is extremely low, if not zero. Weathered bedrock retains a measurable compressive strength even though the may be intensely weathered.

(c) The weathering of the in-place bedrock progressively decreases with depth until it transitions into fresh bedrock. In addition, many of the bedding cross joints become discontinuous as the weathered bedrock transitions into fresh bedrock. Fresh bedrock has a tensile strength, albeit normally more than an order of magnitude less that its compressive strength.

The upper soil-like materials in this zone are generally quite weak and cannot sustain any subsidence induced tensile strain without rupturing. These fragmented materials are stretched as the bedrock they rest on bends downward toward the center of the subsidence trough and then compressed as they reverse the bend as they approach closer to the center of the trough. See **Figure 7. *Critical Panel Width for Maximum Subsidence*** in Affected Environment/Subsidence. The in situ horizontal stress in the soil layer will be the active soil pressure, approximately one-third the gravitational stress at that depth. Longwall mining under weakly-bonded alluvium at similar depths, from 240 to 440 feet, will probably subject the area toward the center of a panel to subsidence induced compressive stress. The compressive stress is commonly evidenced by mounds, as shown on **Figure 15. *Cross Panel Compression Ridge in Alluvium, York Canyon Mine***. In general, when fragmented materials like alluvium once deform in compression the easier it appears to continue deforming at the same location. **Figure 16. *Cross Panel Tension Cracks in Alluvium, York Canyon Mine*** shows a series of sub-parallel tension cracks in fragmental soil-like alluvium. The presence of one tensile crack in alluvium does not necessarily release the tensile strain over any significant distance. The underlying weathered bedrock materials range from extremely weak in tension and compression immediately under the fragmented soil zone layer to much weaker in tension than in compression in fresh bedrock.

The in situ horizontal stress in bedrock is the remaining residual stress within the rock layers in coal bearing formations, such as the Mesaverde Group, present in the swamp deposits at the time of solidification when buried under generally thick shallow sea sediments. The original solidification stress field was probably very close to hydrostatic, equal in all directions. Uplift and erosion has progressively reduced the overburden confining pressure, but not the is situ horizontal pressure. Large shear stress can develop between the vertical and horizontal stresses when uplift and erosion is rapid, and thrust faulting or even major overthrusts may occur when the horizontal stress is released in a short period of geologic time. When uplift is gradual, the shear stress can be released gradually by long-term creep and yielding of the rock toward the lower vertical stress. The time necessary for different rock types to deform (yield) significantly to release the higher horizontal stress was discussed in detail by S. Warren Carey

(1954). The stronger and more competent the rock type, the longer it takes for the shear stress to dissipate. However, the horizontal stress decreases as it approaches the ground surface. The lower the horizontal stress the more readily can the natural bedding cross joints open when the upper part of a layer (bed) is subjected to subsidence induced tensile bending stress.

Large single fractures open at the ground surface when there is only a thin layer of fragmented material above weathered bedrock as was the case for **Figure 17. *Ribside Tension Crack On Steep Slope, York Canyon Mine***. This open fracture follows the offset pattern of two joint sets in the underlying bedrock. **Figure 18. *Ribside Tension Cracks in Road Fill and Cliff Face, York Canyon Mine*** shows a sequence of small tension cracks in the road fill that disappear in the bedrock exposed in a cliff face. The tensile strain was sufficient to open joint blocks and(or) tilt a few of the outer sandstone blocks at the cliff face and topple them onto the roadway.

It should be anticipated that longwall mining under the canyon walls will present a similar hazard for rock to roll out from undermined sandstone outcrops. The slopes of the canyon walls are certainly steep enough within the Red Cliff Mine Project Area to result in thin fragmented soil cover and, therefore, 1-foot wide surface fractures opening when undermined by a longwall panel at the shallower depths, under approximately 500 feet. The conductivity of the valley fill alluvium in the valley bottoms will potentially increase when longwall mining is performed under the valleys. No loss of surface or groundwater into the mine should occur, provided the fracture zone is not intersected.

7.0 PREDICTED SUBSIDENCE OVER THE RED CLIFF MINE PROJECT AREA

The NCB subsidence effects prediction method was used to estimate worst-case maximum vertical subsidence (S_{max}), maximum tensile (+E) and compressive (-E) strains and maximum slope change or tilt (G_{max}) as the result of longwall mining 11 feet of coal at depths of 200 feet, 500 feet, 1000 feet, 1500 feet and 2000 feet employing the potential 800-foot wide, 900-foot wide, 1000-foot wide, 1100-foot and 1200-foot wide longwall panels. In addition, the location of maximum vertical subsidence, maximum tensile strain, maximum compressive strain and maximum slope change with respect to the centerline of the panel conditions described above were calculated. Prediction of the maximum surface fracture widths were made using fracture measurements collected at the York Canyon Mine and NCB calculated tensile strains for the fracture measurement locations relative to the underlying mined longwall panels.

7.1 Maximum Vertical Subsidence (S_{max})

By itself, simply vertically lowering the ground surface would not be a problem. However, the ground surface is only lowered over and near a longwall panel as the coal between the panel headgate and tailgate pillars is progressively extracted and the longwall face is advanced. The surface subsidence trough advances with the longwall face and all sides of the longwall panel deflect downward toward the center of the panel, where the vertical subsidence is maximum. The bending of the overburden develops as the longwall panel progresses and forms a stable semi-permanent trough after the panel is completely mined. The maximum vertical subsidence over a panel is of major importance because it contributes to the magnitude of extension, compression and tilting. These subsidence effects can potentially damage surface and underground structures, infrastructure improvements and hydrologic features as well as potentially adversely impacting nearby overlying and underlying coal seams. All such features have a limited tolerance for these potentially adverse effects. The magnitude of the potentially adverse impacts is directly related to the maximum subsidence, i.e. the greater the subsidence the greater the magnitude of the impact, provided the depth and panel dimensions do not change. The magnitude of the potentially adverse surface impacts is inversely related to the mining depth, i.e. the magnitude of potentially adverse impacts decrease as the mining depth increases. Great Britain has lead the world in researching these relationships because every major metropolitan area, except London, was underlain by multiple mineable coal seams. It is possible to somewhat mitigate the adverse impacts by varying panel width, by designing gateroad pillars between panels to yield when the first of two adjacent panels is mined and crush after the face of the second panel is mined past and by positioning longwall panels with respect to a particularly important surface feature.

The conservative NCB maximum vertical subsidence prediction for supercritical longwall panel widths is 0.9 times the mining height (m) for overburden has been previously subsided. The NCB method specifies that the previously subsided maximum vertical subsidence prediction be multiplied by 0.9 for ground that has not been previously subsided. The adjustment for previously unmined ground is referred to as the “virgin” ground correction in Great Britain. Subsidence over the proposed Red Cliff Mine Project Area was analyzed as virgin ground because none of the proposed lease area appears to have been previously mined. The overall supercritical subsidence factor for virgin ground is 0.81 times the mining height.

The lowering of the ground surface over and around a supercritical longwall panel is trough shaped, as shown on **Figure 4.** ***Plan View of Typical Subsidence Over a Longwall Panel*** in Affected Environment/Subsidence. Figure 4 shows a supercritical width panel with the maximum subsidence (S_{max}) as a narrow area around and along the center of the panel and inside the 1.00 times S_{max} contour line. The maximum subsidence (S_{max}) over a critical or subcritical longwall panel occurs along a line roughly at the center of the panel, as shown on **Figure 7.** ***Critical Panel Width for Maximum Trough Subsidence*** in Affected Environment/Subsidence. **Table 8.** ***Maximum Vertical Subsidence (S_{max}) for Planned Red Cliff Mine Longwall Panels*** presents the S_{max} results of applying **Figure 8.** ***NCB Panel Width/Depth Maximum Subsidence (S_{max}) Prediction*** in Affected Environment/Subsidence and the location of S_{max} with respect to the individual panel centerline through application of **Figure 9**. ***NCB Subsidence Profile Graph*** in Affected Environment/Subsidence. **Figure 19.** ***Maximum Vertical Subsidence (S_{max}) With Respect to Panel Width and Depth*** is a plot of the predicted maximum subsidence for the potential range of panel widths at the anticipated longwall mining depths at the Red Cliff Mine Project Area.

In Table 8, the Panel Width in the first column and Overburden Depth in the second column are given in both English and metric units because the NCB graphs are in metric units. Column 5 presents both the subsidence factor and immediately below the predicted maximum number of feet of vertical subsidence in a parenthesis for the planned maximum 11-foot mining height.

The conservative NCB predicted maximum horizontal tensile (+E) and compressive (-E) strain values presented on **Table 9.** ***Maximum Tensile (+E) and Compressive (-E) Strains for Planned Red Cliff Mine Longwall Panels*** were estimated using **Figure 11.** ***NCB Maximum Strain and Slope Prediction Graph*** in Affected Environment/

Table 8. Maximum Vertical Subsidence (S_{max}) for Planned Red Cliff Mine Longwall Panels.

Panel Width feet (meters)	Overburden Depth feet (meters)	Width/ Depth Ratio (feet)	Supercritical, Critical or Subcritical Panel	S_{max}/m Subsidence Factor (feet)	Smax Distance, from Panel Centerline from (feet)	Centerline to (feet)	Ribside from (feet)	Ribside to (feet)
800 (243.8)	200 (61.0)	4.000	Supercritical	0.810 (8.91)	0	+10	-400	-390
	500 (152.4)	1.600	Supercritical	0.810 (8.91)	0	+25	-400	-375
	1000 (304.8)	0.800	Subcritical	0.681 (7.49)	0	0	-400	-400
	1500 (457.2)	0.533	Subcritical	0.435 (4.79)	0	0	-400	-400
	2000 (609.6)	0.400	Subcritical	0.292 (3.21)	0	0	-400	-400
900 (274.3)	200 (61.0)	4.500	Supercritical	0.810 (8.91)	0	+10	-450	-440
	500 (152.4)	1.800	Supercritical	0.810 (8.91)	0	+25	-450	-425
	1000 (304.8)	0.716	Subcritical	0.716 (7.87)	0	0	-450	-450
	1500 (457.2)	0.600	Subcritical	0.490 (5.39)	0	0	-450	-450
	2000 (609.6)	0.450	Subcritical	0.342 (3.76)	0	0	-450	-450
1000 (304.8)	200 (61.0)	5.000	Supercritical	0.810 (8.91)	0	+10	-500	-490
	500 (152.4)	2.000	Supercritical	0.810 (8.91)	0	+25	-500	-475
	1000 (304.8)	1.000	Subcritical	0.747 (8.22)	0	0	-500	-500
	1500 (457.2)	0.667	Subcritical	0.549 (6.04)	0	0	-500	-500
	2000 (609.6)	0.500	Subcritical	0.396 (4.36)	0	0	-500	-500
1100 (335.8)	200 (61.0)	5.500	Supercritical	0.810 (8.91)	0	+10	-550	-540
	500 (152.4)	2.200	Supercritical	0.810 (8.91)	0	+25	-550	-525
	1000 (304.8)	1.100	Subcritical	0.765 (8.42)	0	0	-500	-500
	1500 (457.2)	0.667	Subcritical	0.598 (6.58)	0	0	-500	-500
	2000 (609.6)	0.500	Subcritical	0.550 (4.85)	0	0	-500	-500

Table 8. Maximum Vertical Subsidence (S_{max}) for Planned Red Cliff Mine Longwall Panels (Cont.)

Panel Width feet (meters)	Overburden Depth feet (meters)	Width/ Depth Ratio (feet)	Supercritical, Critical or Subcritical Panel	S_{max}/m Subsidence Factor (feet)	Smax Distance, from Panel Centerline from (feet)	Centerline to (feet)	Ribside from (feet)	Ribside to (feet)
1200 (365.8)	200 (61.0)	6.000	Supercritical	0.810 (8.91)	0	10	-600	-590
	500 (152.4)	2.400	Supercritical	0.810 (8.91)	0	+25	-600	-575
	1000 (304.8)	1.200	Subcritical	0.788 (8.55)	0	0	-600	-600
	1500 (457.2)	0.667	Subcritical	0.681 (7.13)	0	0	-600	-600
	2000 (609.6)	0.500	Subcritical	0.490 (5.39)	0	0	-600	-600

NOTES: Single panel analysis and positive distances are away from the panel centerline and negative distances are toward the panel centerline.

Table 9. Maximum Tensile (+E) and Compressive (-E) Strains for Planned Red Cliff Mine Longwall Panels.

Panel Width (feet)	Overburden Depth (feet)	Width/ Depth Ratio	Maximum Subsidence S_{max} (feet)	S_{max}/ Depth Ratio	Maximum Extension Multiplier	Maximum Tensile Strain(+E) (υ-strain)	Distance from Centerline (feet)	Maximum Compression Multiplier	Maximum Compressive Strain(-E) (υ-strain)	Distance from Centerline (feet)
800	200	4.000	8.91	0.04455	0.65	29000	400	0.51	22700	235
	500	1.600	8.91	0.01782	0.65	11600	400	0.51	9090	235
	1000	0.800	7.49	0.00749	0.66	4940	417	0.68	5090	110
	1500	0.533	4.79	0.00319	0.78	2490	477	1.25	3990	4
	2000	0.400	3.21	0.00160	0.79	1260	662	1.72	2750	0
900	200	4.500	8.91	0.04455	0.65	29000	450	0.51	22700	264
	500	1.800	8.91	0.01782	0.65	11600	450	0.51	9090	264
	1000	0.900	7.87	0.00787	0.68	5350	460	0.59	4640	190
	1500	0.600	5.39	0.00359	0.75	2690	504	1.05	3770	72
	2000	0.450	4.31	0.00188	0.83	1560	636	1.55	2920	16
1000	200	5.000	8.91	0.04455	0.65	29000	500	0.51	22700	293
	500	2.000	8.91	0.01782	0.65	11600	500	0.51	9090	293
	1000	1.000	8.22	0.00822	0.66	5420	512	0.54	4440	200
	1500	0.667	6.04	0.00403	0.72	2900	537	0.91	3670	117
	2000	0.500	4.36	0.00218	0.82	1790	626	1.37	1790	36
1100	200	5.500	8.91	0.04455	0.65	29000	550	0.51	22700	323
	500	2.200	8.91	0.01782	0.65	11600	550	0.51	9090	323
	1000	1.100	8.42	0.00842	0.66	5470	558	0.52	4380	245
	1500	0.733	6.58	0.00439	0.67	2940	584	0.78	3420	135
	2000	0.550	4.85	0.00242	0.78	1890	642	1.18	2860	66
1200	200	6.000	8.91	0.04555	0.65	29000	600	0.51	22700	352
	500	2.400	8.91	0.01782	0.65	11600	600	0.51	9090	352
	1000	1.200	8.55	0.00855	0.65	5560	608	0.53	4530	289
	1500	0.800	7.13	0.00475	0.66	3140	624	0.68	3230	164
	2000	0.600	5.39	0.00270	0.75	2020	674	1.05	2840	96

Subsidence. The locations of the maximum tensile and compressive strains with respect to the individual panel centerlines were estimated using **Figure 12. *NCB Horizontal Strain Profile Graph*** in Affected Environment/Subsidence. The maximum tensile and compressive strains are important because if they can be conservatively predicted steps can be taken to reinforce critical surface structures or modify the mining plan to reduce the maximum tensile and compressive strains. For example, high pressure natural gas pipelines have been undermined by longwalls by maintaining a smooth pipeline through the period when the trough is forming under the pipeline, while the longwall face advances across or along the pipeline. This has been accomplished by digging up, temporarily supporting the section of the pipeline ahead of the advancing longwall face and reburying the pipeline after the longwall face has advanced well past the elevated section of the pipeline. This procedure prevents the buried pipeline from being pulled apart at an open fracture. Many countries with significant longwall coal mining operations have recommended and(or) established allowable strains for particular surface features. Some of these are included in **APPENDIX A. RECOMMENDED LIMITS FOR SUBSIDENCE INDUCED STRAIN AND TILT**.

7.2 Maximum Horizontal Strain

The maximum horizontal tensile strains are the most serious potential hazard with respect to anticipated subsidence impacts from longwall mining in the proposed Red Cliff Mine lease area. This involves protecting the public from larger open fractures, as shown on **Figure 20. *Tension Crack Over Starter Room, York Canyon Mine***, when longwall mining at shallow depths (<500 feet). There is also the temporary potential for large boulders being dislodged from sandstone cliffs on the canyon walls by smaller tensile strains from deeper active longwall panels, as indicated on **Figure 18. *Ribside Tension Cracks in Road Fill and Cliff Face, York Canyon Mine***.

Table 10. *Predicted Surface Fracture Widths Based on York Canyon Mine Measurements* presents the relationship between predicted tensile strain and the measured width of selected open subsidence fractures above three longwall panels at the York Canyon Mine west of Raton New Mexico. The York Canyon Mine was mining coal in the Mesaverde Group, but the overburden lithology could well differ from that present at the Red Cliff Mine proposed Project Area.

The horizontal tensile strain over the barrier pillars between panel groups will probably increase because the strain at the surface over the barrier pillar caused by each adjacent panel is additive. It is possible that the maximum horizontal tensile strain above the larger barrier pillars planned between panel groups could as much as double the tensile strain on the surface over the center of such a barrier pillar. This is possible because it depends on the panels on both sides being subcritical precisely enough to place the maximum tensile strain at the center of the barrier pillar. For example, using **Figure 12. *NCB Horizontal Strain Profile Graph*** in Affected Environment/Subsidence, the center of a 1000-foot wide panel at the depth of 2000 feet (Panel Width/Depth Ratio = 0.500) is 600 feet from the center of a 200-foot wide barrier pillar, 0.300 times the 2000-foot depth. The predicted tensile strain over the center of the barrier pillar from the first longwall panel to be completed on one side of the group barrier pillar is 95% of the predicted maximum horizontal tensile strain. If a longwall panel group with the same dimensions and depth is mined on the other side of the barrier pillar is completed it would add 95% of its maximum horizontal tensile strain at the center of the 200-foot barrier pillar, nearly doubling (approximately 1.9 times) the tensile strain at that location,

Table 10. Predicted Surface Fracture Widths Based on York Canyon Mine Measurements.
Assumes virgin ground and 11-foot mining height.

Panel Width (feet)	Overburden Depth (feet)	Width/ Depth Ratio	Maximum Subsidence (feet)	Maximum Tensile Strain (υ-strain)	Open Fracture Width (inches)	Predicted Distance from Centerline (feet)	Predicted Distance from Ribside (feet)
800	200	4.000	8.91	29000	19.8	400	0
	500	1.600	8.91	11600	7.8	400	0
	1000	0.800	7.49	4940	3.2	417	17
	1500	0.533	4.79	2490	1.5	477	77
	2000	0.400	3.21	1260	0.7	662	262
900	200	4.500	8.91	29000	19.8	450	0
	500	1.800	8.91	11600	7.8	450	0
	1000	0.900	7.87	5350	3.5	460	10
	1500	0.600	5.39	2690	1.7	504	54
	2000	0.450	3.76	1560	0.9	636	186
1000	200	5.000	8.91	29000	19.8	500	0
	500	2.000	8.91	11600	7.8	500	0
	1000	1.000	8.22	5420	3.5	512	12
	1500	0.667	6.04	2900	1.8	537	37
	2000	0.500	4.36	1790	1.0	626	126
1100	200	5.500	8.91	29000	19.8	550	0
	500	2.200	8.91	11600	7.8	550	0
	1000	1.100	8.42	5470	3.6	558	8
	1500	0.733	6.58	2940	1.8	584	34
	2000	0.550	4.85	1890	1.1	642	92
1200	200	6.000	8.91	29000	19.8	600	0
	500	2.400	8.91	11600	7.8	600	0
	1000	1.200	8.55	5560	3.6	608	8
	1500	0.800	7.13	3140	2.0	624	24
	2000	0.600	5.39	2020	1.2	674	74

NOTE: Single panel subsidence analysis.

and similarly increase the width of the predicted open fracture. The total additive tensile strain at other locations along the overlapping strain profiles could be conservatively predicted by superimposing the subsidence profiles from the two adjacent longwall panels. The rapidly changing overburden depths at the Red Cliff Mine Project Area could make estimating the total tensile strains across barrier pillars using the NCB method a time consuming process.

7.3 Maximum Tilt (G)

The maximum slope or tilt change as the result of mining a longwall panel occurs at the inflection point between bending progressively more downward toward the center of the panel to bending progressively less downward closer to the center of the panel. On **Figure 4. *Plan View of Surface Subsidence Over a Longwall Panel*** in Affected Environment/Subsidence, this is the 0.50 S_{max} contour line. With the exception of subcritical panels, where the panel width is less than approximately 0.41 times the panel depth, the inflection line is within the sides of the panel projected to the ground surface. **Table 11. *Maximum Slope Angle (Tilt) Change for Planned Red Cliff Mine Longwall Panels*** lists potential panel widths, depths, panel width/depth ratios and the slope (tilt) change multiplier from **Figure 10. *NCB Maximum Strain and Slope Prediction Graph*** in Affected Environment/Subsidence. The calculated maximum slope angle change is presented in terms of percent grade change and degrees.

The conservative NCB predicted single panel maximum slope angle changes resulting from longwall mining of the proposed Red Cliff Mine Project Area, potentially ranging from approximately 0.5% to 12% (0.3^o to 7^o) would present significant hazards to overlying industrial, business and residential uses. However, no such land uses are planned over the Red Cliff Mine. The principal tilting hazard posed to the undeveloped surface overlying the proposed lease area by longwall mining would appear to be tilting cliff forming sandstone beds outcropping on the canyon walls and potentially toppling sandstone boulders toward the canyon floors. **Figure 18. *Ribside Tension Cracks in Road Fill and Cliff Face, York Canyon Mine*** show a sandstone cliff failure in the combined downslope tilted and tension zone approximately 50 feet outside the underlying longwall panel ribside.

Table 3. *Slope Geometries Within Project Area* lists some of the higher overall canyon slopes in the lease area. The slopes of Big Salt Wash canyon, the major canyon in the proposed lease area, walls are as high as 920 feet and as steep overall as 32^o, which is the most impressive combination in the Project Area. It is possible to at least partially mitigate this and similar potential major toppling hazards in Garvey Canyon and along Munger Creek by retreating toward these drainages from the north and from the south. Retreating toward these drainages, would slightly flatten the slope of the canyon walls as opposed to advancing away from Big Salt Wash which would slightly steepen the canyon walls. See **Figure 9. *Localized Mining Induced Slope Angle Changes***.

The slope angle or tilt change over a barrier pillar is not additive like horizontal tensile strains over barrier pillars. The slope angle or tilt change coming from longwall panels on opposite sides of a barrier pillar are in opposite directions Therefore, where the tilting overlaps the longwall mining induced slope changes at least partially cancel each other. The maximum interaction is potentially possible complete cancellation is unlikely.

Table 11. Maximum Slope Angle (Tilt) Change for Planned Red Cliff Mine Longwall Panels.

Panel Width (feet) (feet)	Overburden Depth (feet)	Width/ Depth Ratio	S_{max}/ Depth Ratio	Slope (Tilt) Multiplier	Maximum Slope or Tilt Angle (%)	(°)	Predicted Distance from Centerline	from Ribside (feet)
800	200	4.000	0.04455	2.73	12.16	6.93	325	-75
	500	1.600	0.01782	2.73	4.86	2.78	325	-75
	1000	0.800	0.00749	2.82	2.11	1.21	288	-112
	1500	0.533	0.00319	3.27	1.04	0.60	315	-85
	2000	0.400	0.00160	3.37	0.54	0.31	412	12
900	200	4.500	0.04455	2.73	12.16	6.93	366	-84
	500	1.800	0.01782	2.73	4.86	2.78	366	-84
	1000	0.900	0.00787	2.76	2.17	1.24	327	-123
	1500	0.600	0.00359	3.12	1.12	0.64	336	-114
	2000	0.450	0.00188	3.45	0.65	0.37	400	-50
1000	200	5.000	0.04455	2.73	12.16	6.93	407	-93
	500	2.000	0.01782	2.73	4.86	2.78	407	-93
	1000	1.000	0.00822	2.75	2.26	1.29	373	-127
	1500	0.667	0.00403	2.97	1.20	0.69	363	-137
	2000	0.500	0.00218	3.37	0.73	0.42	407	-93
1100	200	5.500	0.04455	2.73	12.16	6.93	447	-103
	500	2.200	0.01782	2.73	4.86	2.78	447	-103
	1000	1.100	0.00842	2.74	2.31	1.32	416	-134
	1500	0.733	0.00439	2.87	1.26	0.72	392	-158
	2000	0.550	0.00242	3.24	0.78	0.45	427	-123
1200	200	6.000	0.04455	2.73	12.16	6.93	488	-112
	500	2.400	0.01782	2.73	4.86	2.78	488	-112
	1000	1.200	0.00855	2.74	2.34	0.45	459	-151
	1500	0.800	0.00475	2.82	1.34	0.77	431	-169
	2000	0.600	0.00270	3.12	0.84	0.48	448	-152

NOTE: Positive distances are away from the panel centerline and negative distances are toward the panel centerline.

7.4 Angle of Draw

The angle of draw defines the extent that subsidence can be detected beyond the limits of mining. The angle of draw is the angle formed by the vertical line above the outer limit of mining and the lateral limit of detectable subsidence. It has special importance to land-use planning because it indicates where the surface will be unaffected by mining-induced subsidence. Reported angles of draw are highly variable, as indicated by **Table 6. *Angles of Draw for Coal Mining in the United States and Europe*** which presents angles of draw from 19^{o} to 45^{o} collected from various countries and sources. The study by Abel and Lee (1984) demonstrated that the potential for error in applying the angle of draw measured in one country to another, or even within one country and(or) district, is considerable. **Table 12. *Angles of Draw for Mines in Flat-Bedded Sedimentary Rocks with Respect to Lithology of Overburden***, from their paper, shows a wide range of angles of draw, from 0^{o} to 40^{o}, indicates that lithology statistically appears to plays a roll in determining the angle of draw. The various sources of data demonstrate that the NCB's 35^{o} angle of draw is a conservative estimate.

7.5 Break Angle

The historic concept of a break angle as the location of the tensile surface cracking has been discarded because it coincides with the location of maximum tensile strain (+E). In areas of thick soil or alluvium, tensile cracking at the surface may be difficult to see because the tensile strain typically produces several narrow cracks, as can be seen on **Figure 18. *Ribside Tension Cracks in Road Fill and Cliff Face, York Canyon Mine***. Narrow cracks fill rapidly because the alluvium contains fines and has little tensile strength.

When bedrock is close to the surface, the easiest tensile crack to see open is over the starter room, because it initially increases in width and doesn't close as the longwall face advances. Cracks on the surface over a starter room are usually the first to open and take a long time to fill by the natural processes of weathering, mass wasting, and erosion. The tensile crack accompanying the advance of the longwall face is mobile, i.e. it advances as the longwall face advances. However, the opening of bedding cross joints in the moving tensile strain zone ahead of an advancing underlying longwall face is temporary. These tensile cracks start to close after the longwall face has passed about 0.15 times the depth (approximately 8^{o}) and the horizontal compressive strain starts. Closure in the compressive strain zone reaches a maximum when the longwall face is approximately 0.3 times the depth past the tensile fracture. **Figure 15. *Cross Panel Compression Ridge in Alluvium, York Canyon Mine*** shows a compression mound that was pushed up when the soil that fell into the initial tension crack was compressed by the trailing compression zone.

Similarly, the tensile strain zones on the ground surface roughly over the panel ribsides, starter room and eventually the shield recovery room is relatively easy to see as it develops. As the longwall face passes a position on the surface overlying any location along either gateroad the tensile crack, or cracks, develop. After the longwall face has advanced approximately 0.7 times the depth the trough and associated tensile crack remains open, as shown on **Figure 17 *Ribside Tension Crack On Steep Slope, York Canyon Mine***.

Table 12. Angles of Draw for Mines in Flat-Bedded Sedimentary Rocks with Respect to Lithology of Overburden
(Abel and Lee, 1984)

Location, Commodity	Lithologic Percentages in Overburden			Angle of Draw (degrees)[2]	References
	Shale[1]	Sandstone	Limestone		
Pennsylvania coal.	50	22	28	18.0	Greenwald and others (1937).
Do----------------------	78	13	9	24.0	Maize, Thomas, and Greenwald (1940).
Do----------------------	59	11	30	9.0	Maize and Greenwald (1939).
New Mexico coal.	63	37	0	15.0	Abel and Gentry (1978).
Great Britain coal.	12	88	0	0.0	English (1940).
Do----------------------	68	32	0	17.0	Sinclair (1950).
Do----------------------	63	29	8	12.0	Do.
Do----------------------	64	36	0	29.0	Briggs and Ferguson (1933).
Do----------------------	51	48	1	16.5	Thorneycroft (1931).
New Mexico uranium.	86	14	0	40.0	C. H. Parrish written commun., 1979).
California borate [3]	17	83	0	8.0 (avg.)	Obert and Long (1962).
Pennsylvania coal.	48	52	0	18.0	Montz and Norris (1930).
India coal.	25	75	0	13.0	Kumar and Singh (1973).
Do----------------------	23	77	0	21.0	Do.
Do----------------------	57	43	0	28.0	Do.
Do----------------------	37	63	0	18.0	Do.
Do----------------------	35	65	0	17.0	Do.
Do----------------------	35	65	0	17.0	Do.
Do----------------------	23	77	0	17.0	Do.
Do----------------------	32	68	0	27.0	Do.
Illinois coal.	71	17	12	8.5	Herbert and Rutledge (1927).
Do----------------------	57	38	5	0.0	Do.
Do----------------------	85	9	6	34.7	Auchmuty (1931).
Arizona copper.	0	0	100	12.0	Trischka(1934)[3].

'Includes all argillaceous rocks. [2]Angles measured from vertical.
[3]Fault bounded on all four sides. Therefore, not employed in statistical analysis.

7.6 Rate and Duration of Subsidence

The first potentially detectable subsidence at a given point on the ground surface ahead of an approaching longwall face begins when the longwall face is something less than approximately 0.75 times the overburden depth of the seam, has subsided about 15% of S_{max} when the longwall face passes under the point, is approximately 50 percent complete when the longwall face is 0.2 to 0.3 times the overburden depth beyond the point, and appears to have stopped subsiding when the face is between 0.5 and 0.6 times the overburden depth beyond the point. However, there is still 5% to 9% of residual subsidence to take place after the longwall face has either mined beyond the influence distance or the panel has been completed. Residual subsidence is probably the result of consolidation of the gob and closure of some overlying bed separations in the overburden. Measuring the time until residual subsidence is complete requires extremely precise leveling to measure subsidence. Collins (1977) reported the results of an eight year program in the South Wales Coalfield. He reported the results from six panels at depths from 207 feet to 2330 feet. Longwall mining of the six panels was completed over periods from 0.5 to 1.5 years and measurable residual subsidence continued for 2.0 to 4.5 years afterwards. Complete stability is not significant because the potentially damaging strains and tilt are directly dependent on the magnitude of the subsidence and the magnitude of residual subsidence is small in relation to the subsidence that takes place during the active period.

Shortly after the advancing longwall face has opened up enough area to initiate the first major roof cave behind the shields, the wave of surface subsidence accompanying face advance will start. The movement of the longwall face and the ground surface are so closely tied together that when the advance of the face stops the advance of the accompanying wave of surface subsidence advance may stop in less than a shift, but definitely over a weekend. Stopping the advance of a longwall face will, however, potentially increase the loads on the face supports. Sloughing from the coal face can also occur during stoppages. Restarting face advance after holiday periods, etc. can be difficult.

Peng (1992, p. 20-22) reports maximum dynamic tilt and horizontal strain decreases with increasing speed of longwall extraction. Peng presents graphical data for the rate of face advance for various longwall faces in a West Virginia coal mine which increased from roughly 10 feet/day to roughly 43 feet/day:

1. Maximum dynamic tilt appears to have decreased an average of approximately 44 percent (Peng, 1992, Fig. 3.6). The scatter of the dynamic tilt data is so large and the contradictory indication of an increasing maximum dynamic tilt for the single most rapid 43 feet/day face advance indicated on Fig. 3.6 that it appears statistically only possible to state that the tilt probably decreased with increasing face advance rate.

2. Maximum dynamic tensile strain decreased by an average of approximately 28 percent (Peng, 1992, Fig. 3.7). The scatter of the dynamic tensile strain data indicated on Fig. 3.7 is less than for the dynamic tilt data and it may be statistically possible to indicate a rough numerical relationship between decreasing tilt and increasing face advance rate.

3. Maximum dynamic compressive strain decreased by an average of approximately 62 percent (Peng, 1992, Fig. 3.8). The scatter of the dynamic compressive strain data indicated on Fig. 3.8 is nearly as large as that for the dynamic tilt data. It appears statistically possible to state that the maximum dynamic compressive strain decreased with increasing face advance rate.

8.0 IMPACTS OF SUBSIDENCE ON STRUCTURALLY SENSITIVE AREAS

8.1 Longwall Mining in Geologic Hazard Areas of Landslides, Rockfalls, and Unstable Slopes

These unstable areas occur naturally on steep canyon walls in the Mesaverde Group. Unstable slope features already present can be adversely impacted by longwall mining.

- It is important to develop an inventory of baseline data on any landslide, rockfall, and generally unstable areas before mining begins, so that movements due to natural processes can be excluded from any potential mining impacts if they would create a hazard to the public.

- It is also important to have an assessment plan to distinguish between mining-related impacts on existing unstable areas and other activities, such as road construction. The assessment plan should include a subsidence monitoring program which should indicate the maximum angle of draw to the maximum limit of subsidence effects for the Red Cliff Mine Project area.

- Tilt and strain caused by subsidence may reactivate movement in a currently stable or dormant landslide and rockfall areas where slope movements would be expected to eventually naturally reoccur due to natural causes. In the case of unstable natural slopes they are most likely to develop, reoccur and grow on steeper slopes during periods of increased precipitation. If a dormant landslide or rockfall area starts moving during a dry period and within approximately 0.7 times the depth distant from an advancing longwall face, the movement has very likely to have been triggered by the mining.

- Large tilt and horizontal strain values caused by longwall mining under the shallower overburden, close to the coal outcrop or on the lower sections of steep canyon walls on the southwest side of the Project Area, could potentially cause the greatest mining impacts on areas that are already unstable.

    1. Tilt values greater than about 5 percent, with approximately 500-foot overburden depth or less, may impact areas that are already prone to landslides or rockfalls, particularly where the tilt direction parallels the downslope direction, and, therefore, increases the overall slope angle by roughly the maximum predicted tilt amount. See Figure 9 C and Figure 18.

    2. The stability of geologic hazard areas may also be increased by subsidence, where the subsidence induced tilt direction is opposite to the topographic slope direction. In this instance, the overall slope angle would

be decreased by as much as the maximum subsidence-induced tilt change. See Figures 9B.

3. Horizontal tensile strain values generally greater than approximately 1 percent (10000 υε) at 500-foot overburden depths and less also may accelerate natural landslide movement or rockfall, particularly during periods of high or increased precipitation. **Figure 18. *Ribside Tension Cracks in Road Fill and Cliff Face, York Canyon Mine*** shows a location where a sandstone cliff face failed after some of the shale underlying a sandstone cliff face had been removed for the pioneer road and then the headgate end of the longwall panel was mined past at approximately 360 feet below but over 50 feet to the right of the cliff. The estimated non-maximum tensile strain acting on the cliff face was about 0.5 percent (~5000 υε).

8.2 Mining Beneath Stream Courses

The only permanent stream courses indicated on the Garvey Canyon Quadrangle and Howard Canyon Quadrangle for the Project Area are Big Salt Wash and East Salt Creek. Big Salt Wash is the only perennial stream that overlies planned Red Cliff Mine workings in the Cameo Seam. East Salt Creek does not cross over any part of the Cameo Seam within the Existing Coal Lease or Coal Lease Application area. The Cameo Seam outcrop crosses Big Salt Wash approximately 7,800 feet upstream from the southern boundary of the Coal Lease Application area, as shown on **Figure 13. *Overburden and Outcrop Map for the Project Area***.

Within the Existing Coal Lease area, the Cameo Seam outcrop crosses the intermittent stream course in Stove Canyon, Section 2, T. 8 S., R102 W. northwest of Big Salt Wash and the intermittent stream courses in Munger Canyon and its southeast tributary, Sections 22 and 27, S. 7 S., R. 102 W. These Cameo Seam outcrops are within the Project Area.

Within the Coal Lease Application area the Cameo Seam outcrop crosses the intermittent stream course in Buniger Canyon approximately 4,500 feet upstream from where it meets the perennial stream in Big Salt Wash.

In order to mitigate potential subsidence impacts in the Coal Lease Application area and the immediately adjacent north, east and south parts of the Project Area, it was necessary to have a conceptual mining plan. The goals of the conceptual plan were to maximize safety, then mitigate to the extent possible subsidence impacts and finally to maximize resource recovery. The proposed portal is the anchor for the concept. The conceptual plan that follows involves at least two sets of east-west mains driven off the Big Salt Wash mains. A bleeder entry may well be necessary along the south boundary of the Project Area. Either a bleeder entry or a third set of mains would probably be required along the northern boundary of the Project Area.

It will be necessary to drive the main access entries approximately 5,000 feet N 45^{o} E from the planned Red Cliff Mine portal to where it will cross under the overlying intermittent stream course in Stove Canyon at a depth of less than 200 feet., The main entries will probably continue to a distance of approximately 9,000 feet where it will cross beneath the intermittent stream course in Buniger Canyon at a depth of slightly less than

500 feet, still within the Existing Coal Lease area. The N 45^{o} E direction of the Red Cliff Mine main entries indicates that the Main entries will probably turn half-right after passing under Buniger Canyon to drive east just south of the boundary between T. 7 S. and T. 8 S. Driving the mains in this direction would reach Big Salt Wash in approximately 8,200 feet at a depth of approximately 200 feet.

It is anticipated that the main entries will split at Big Salt Wash with one branch continuing to the east, the 1st East Mains, and the other driven to the northeast under Big Salt Wash, the Northeast Mains. The East Mains would be the base for developing longwall panels as much as 14,000 feet to the south. If no longwall panels are driven to the north it could be possible to rob the barrier and main entry pillars on the retreat provided the retreat mining was protected by unmined coal on the north side of the 1st East Mains. This assumes that the individual longwall panels driven south off the 2nd East Mains are mined after the 2nd West Mains and that the 2nd East Mains longwall panels are sequenced from east to west and retreated from south to north following the retreat of the 1st East Mains pillars.

Retreat mining the 2nd West Mains and the 2nd East Mains would probably require a third set of main entries driven from East Salt Creek or Munger Creek and across the north end of the Project Area.

Mining beneath the perennial and intermittent stream courses will necessitate preventing water loss to the underlying workings. As discussed previously in section 6.1.2 Fractured Zone, water loss to the fracture zone is probable through 100 feet or less of overburden when longwall mining in the Red Cliff Mine Project Area. Big Salt Wash is particularly at risk because it also contains a road and has agricultural uses. Because there is no available depth of alluvium below any of the deeply incised canyons and the absence of any data on the potential fault control of the nearly trellis drainage pattern in the Project Area, conservatism must be used and a minimum of 200 feet of overburden required to positively prevent water loss from longwall mining under even intermittent stream courses. **Table 10. *Predicted Surface Fracture Widths Based on York Canyon Mine Measurements*** provides conservative estimates of fracture widths with respect to depth of overburden and panel width.

9.0 SURFACE SUBSIDENCE MONITORING

Various governmental bodies may require a monitoring demonstration that the predicted subsidence effects are indeed conservative and not significantly exceeded. Specifically, a monitoring program over one of the initial longwall panels that will obtain subsidence data on the maximum vertical subsidence (Smax), tensile (+E) and compressive (-E) horizontal strains, angle of draw (α) and subsidence induced tilt (G) for this unique geologic environment. If room-and-pillar panels are mined it may be necessary to measure the same subsidence effects, or to demonstrate that sufficient pillars are left to prevent subsidence.

The Surface Subsidence Monitoring Guidelines by Abel (1982) indicate one possible monitoring program that has been utilized to provide the data, when required. **Figure 21. *Subsidence Monitoring Program*** indicates the location of surface monuments for flat lying terrain. The rugged terrain and rapidly changing overburden depth in the Project Area will necessitate panel-by-panel monument spacing modifications in the field after the locations of the initial panels become available. Either monument spacing for the test panel will have to be continuously changed to match overburden changes or all monuments will have to be spaced to match the shallowest overburden for that panel. Considerable advances have been made since the early subsidence transit and leveling monitoring programs by the NCB. The precise leveling used by Collins (1977), has been replaced by Electronic Distance Measurement (EDM) and more recently the Global Positioning System (GPS) has apparently increased its accuracy to the point that it has been used to measure subsidence induced changes at the ground surface. There is no substitute for properly constructed monuments either anchored to bedrock or at sufficient depth to prevent temperature and moisture changes from impacting the measurements.

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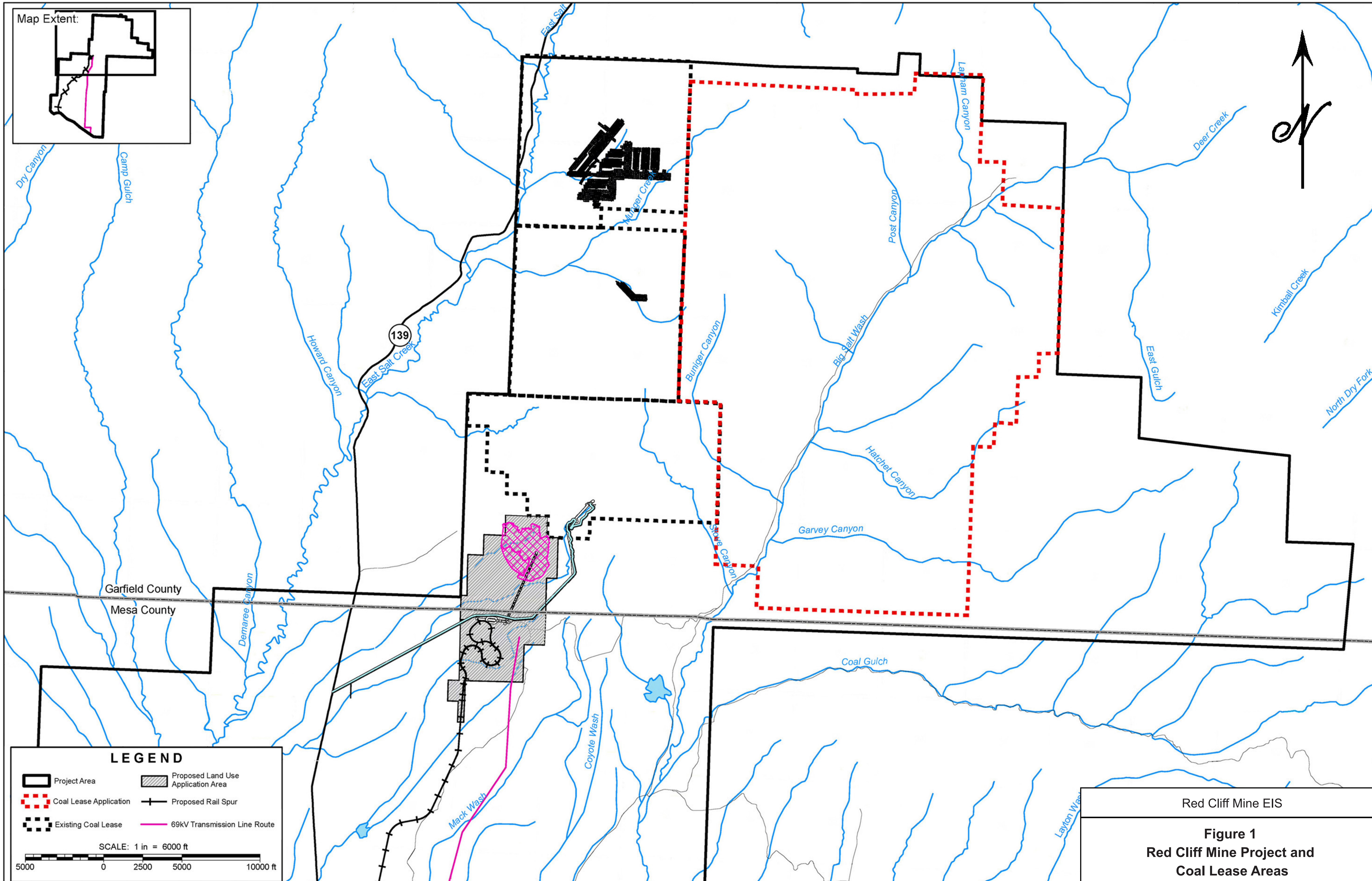
11.0 FIGURES



Red Cliff Mine EIS

Figure 1
Red Cliff Mine Project and Coal Lease Areas

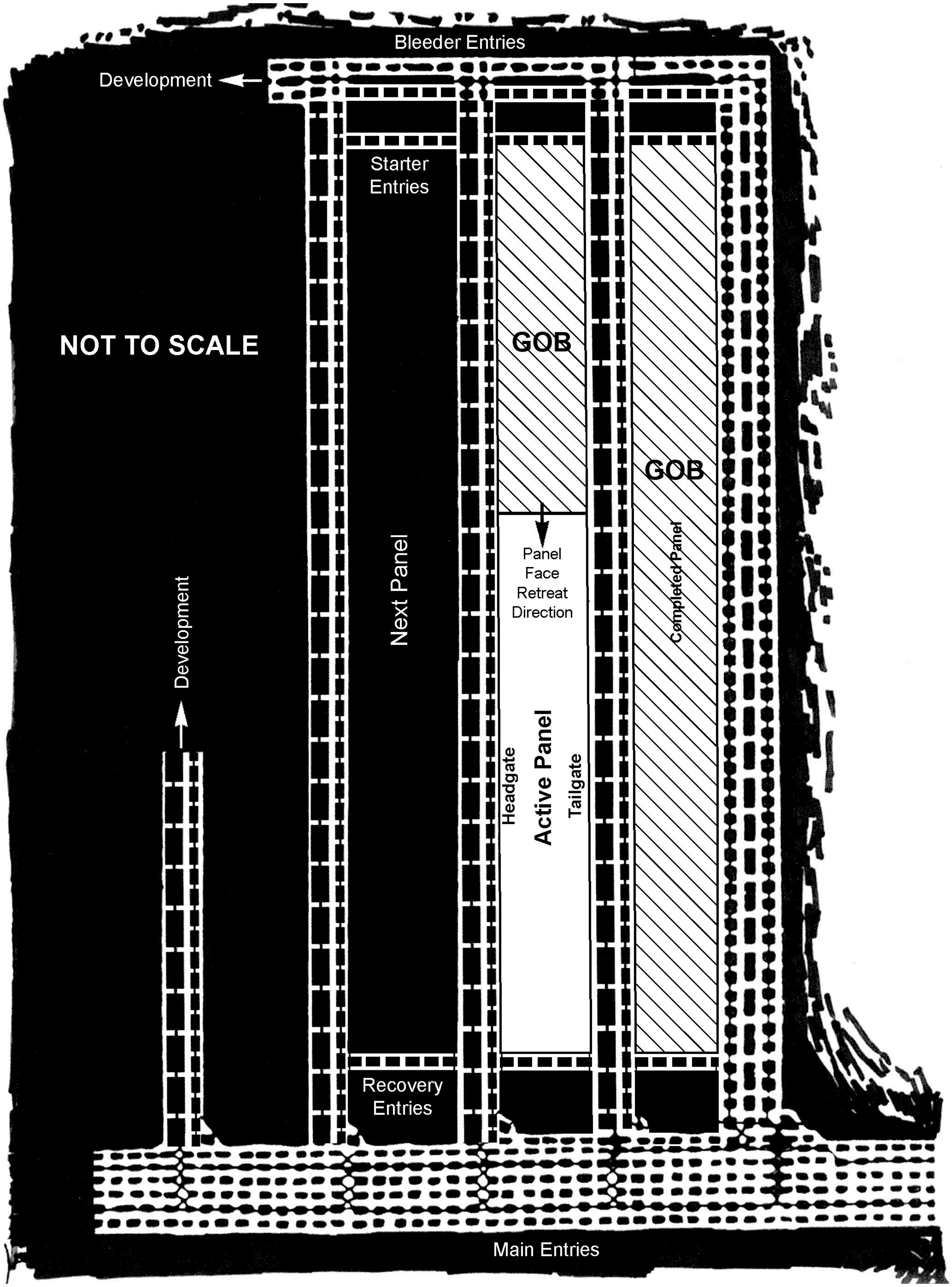


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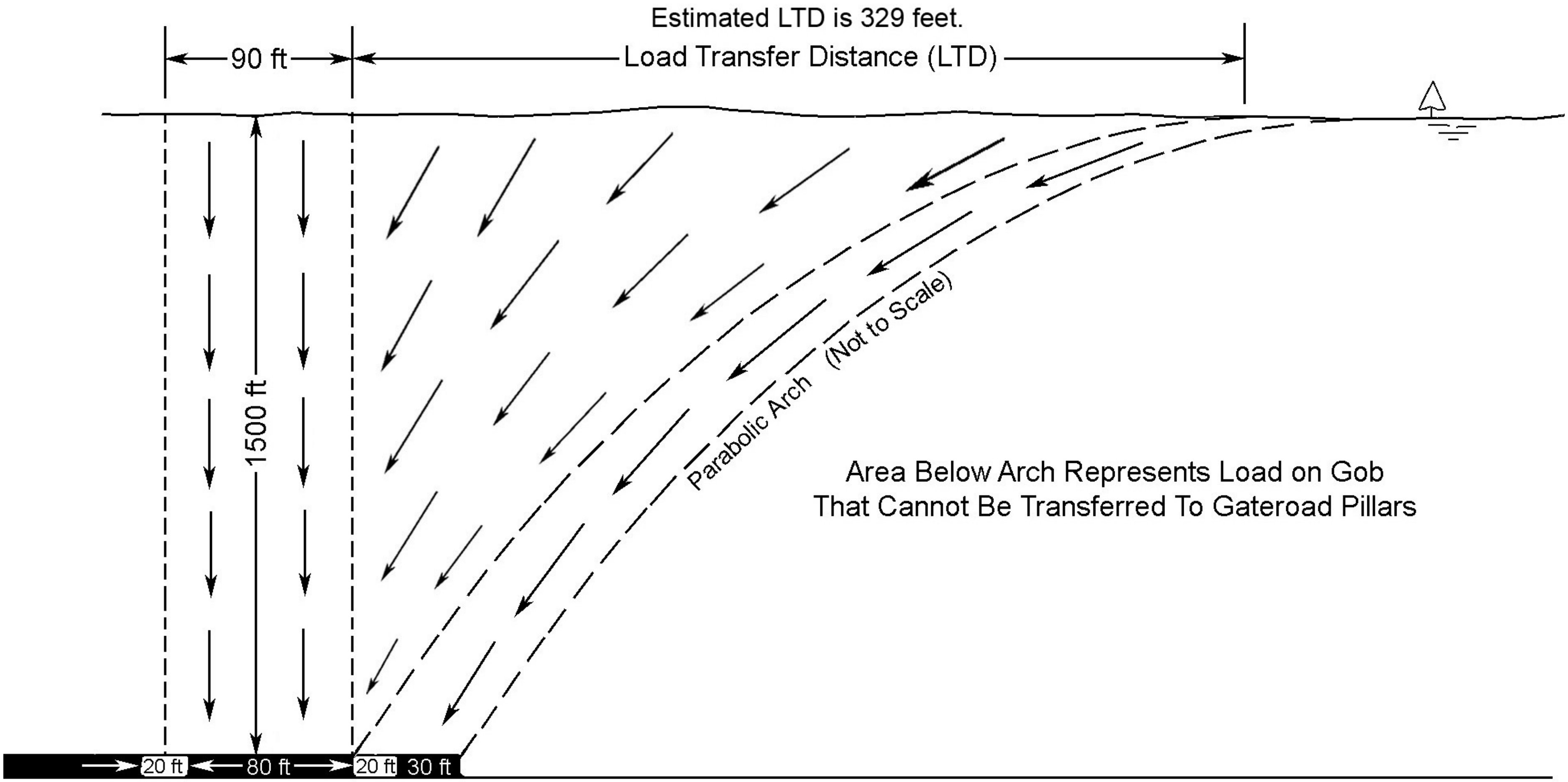
Figure 2
Plan View of Three Adjacent Longwall Panels



Estimated rigid pillar design load on 80-ft wide by 180-ft long pillar for 160 PCF overburden is 4,792,000 tons and average pillar stress is 4620 psi. Estimated minimum yield pillar load for 30-ft wide by 80-ft long pillar is 600,000 tons and average pillar stress is 3470 psi.

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Figure 3
Estimated Gateroad Pillar Loads from Mining First Adjacent Panel

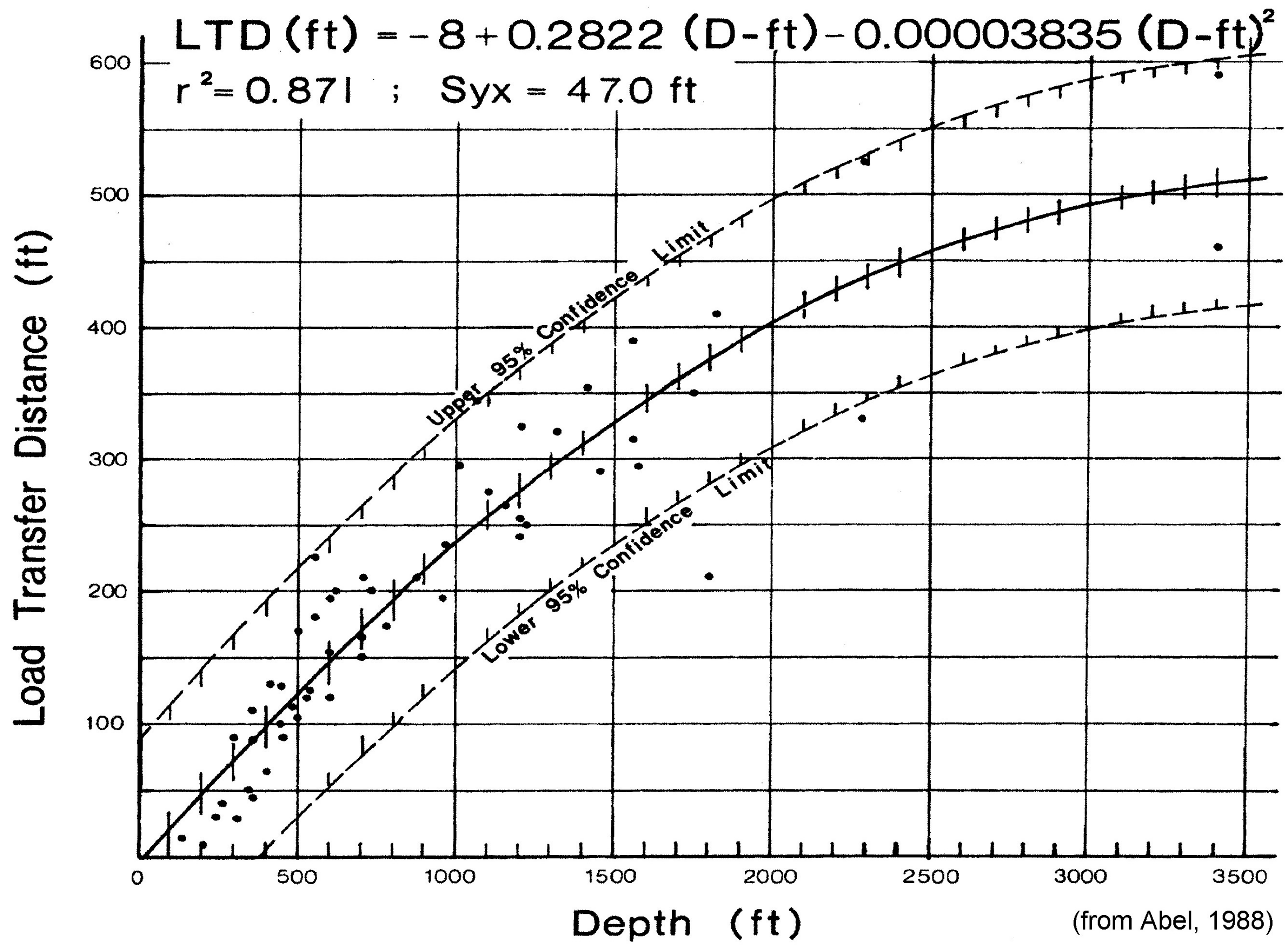

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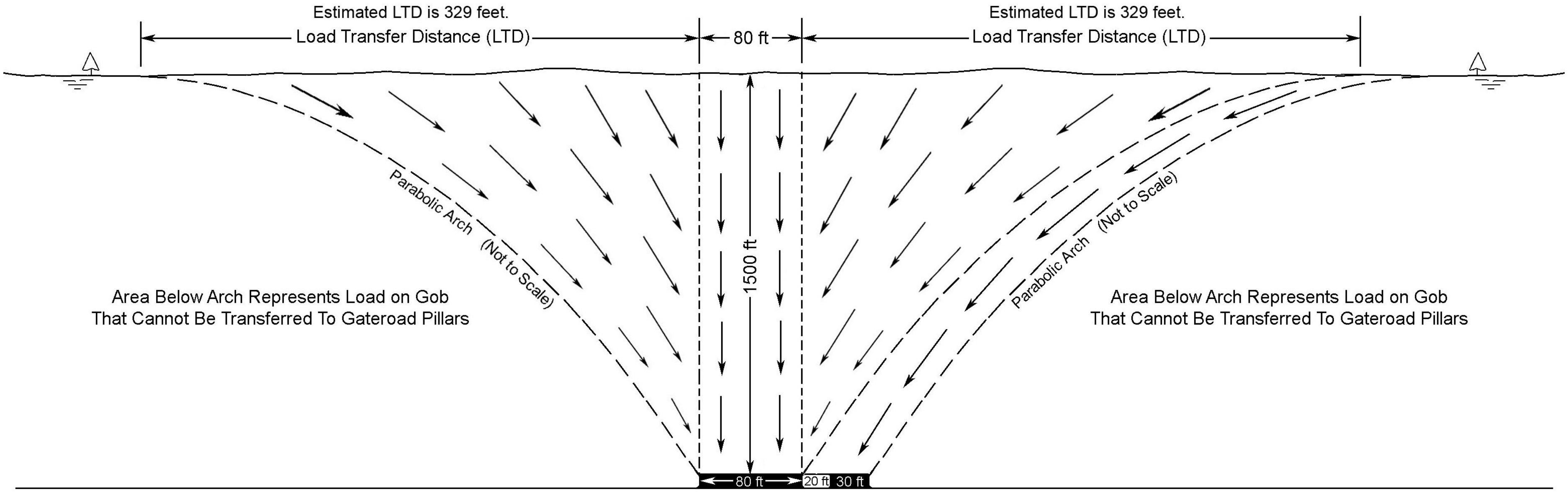
Figure 4
Load Transfer Distance Data

Theoretical design loads and stresses on rigid and yield pillars after passage of second adjacent panel.



Estimated minimum rigid pillar design load on 80-ft wide by 180-ft long pillars for 160 PCF overburden is 7,184,000 tons and average pillar stress is 6930 psi. Estimated minimum yield pillar load is 600,000 tons and average pillar stress is 3470 psi.

Red Cliff Mine EIS

Figure 5
Estimated Gateroad Pillar Loads from Mining Second Adjacent Panel

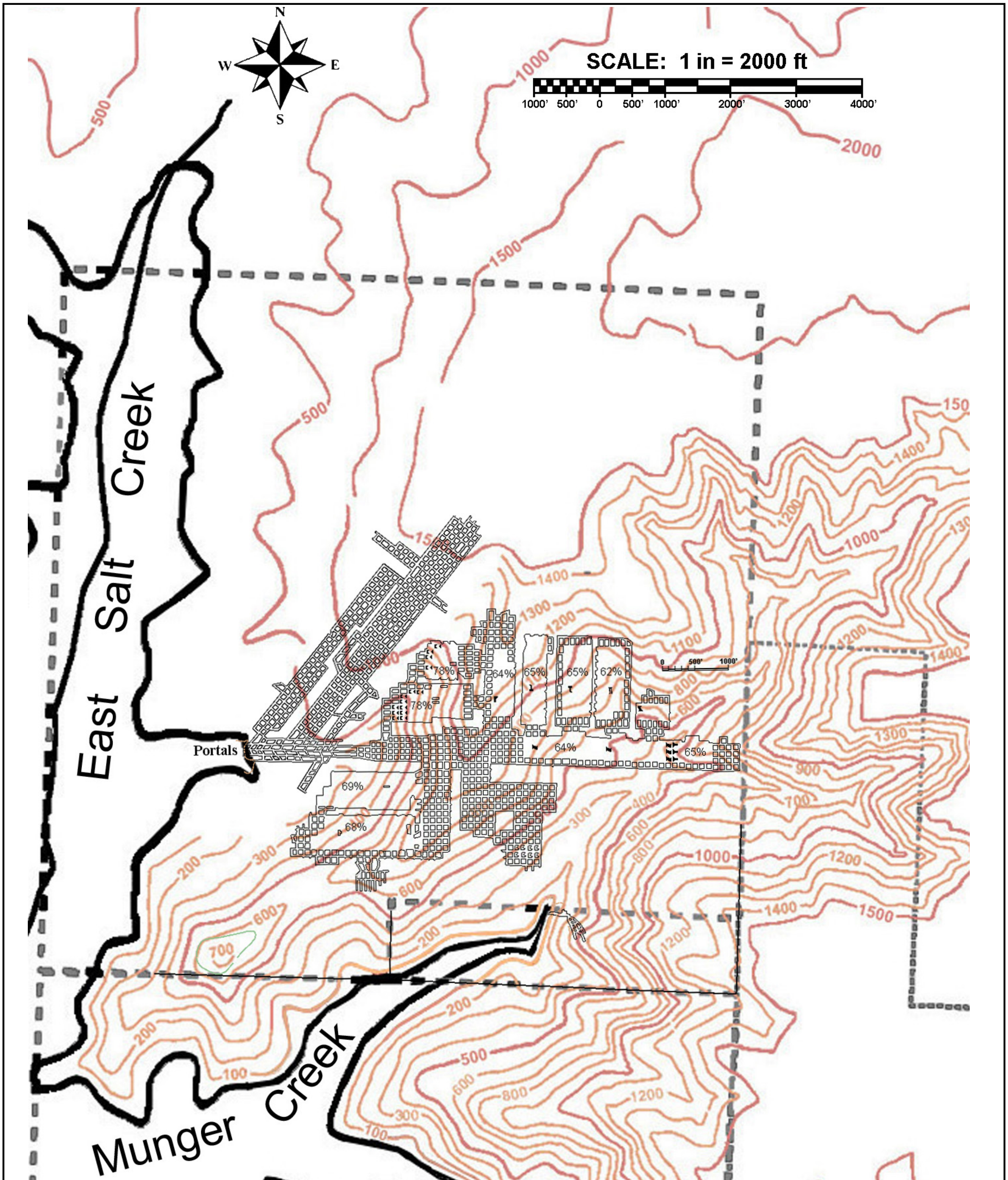


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Figure 6
McClane Canyon
Mine Workings

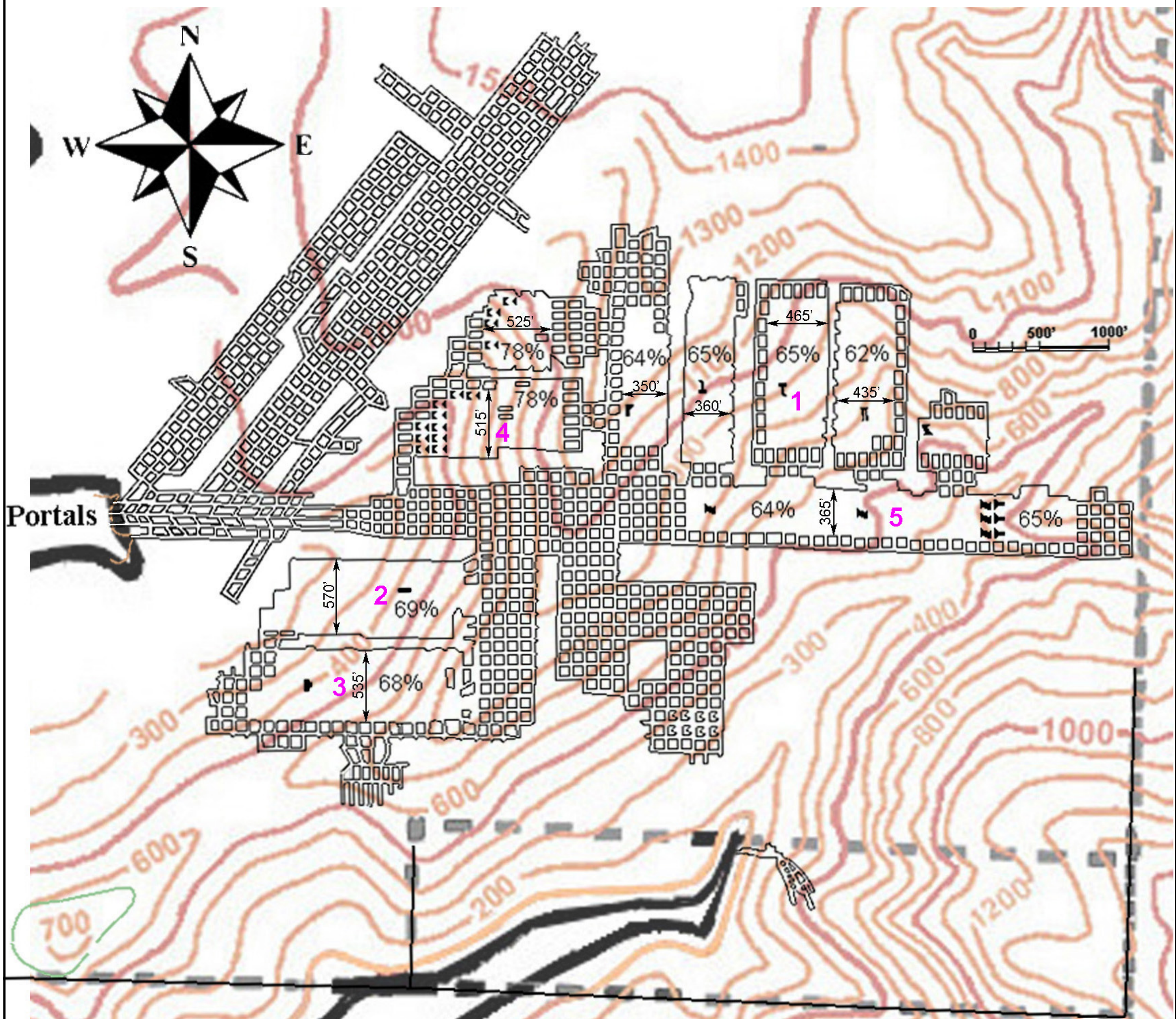

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Figure 7
Subsidence Predicted for Five Selected Panels, McClane Canyon Mine

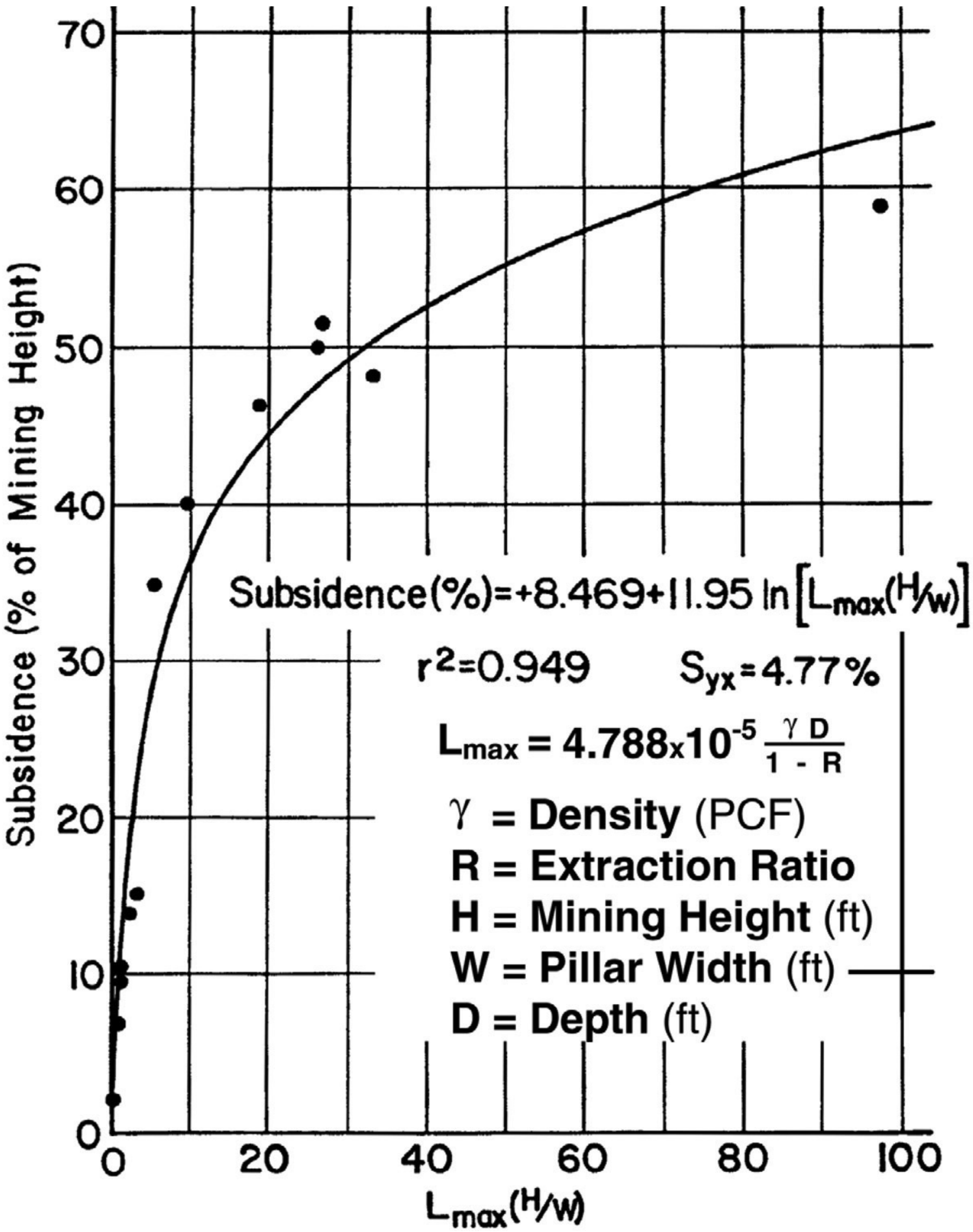

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Figure 8
Subsidence Over Room-and-Pillar Workings after Pillar Failure

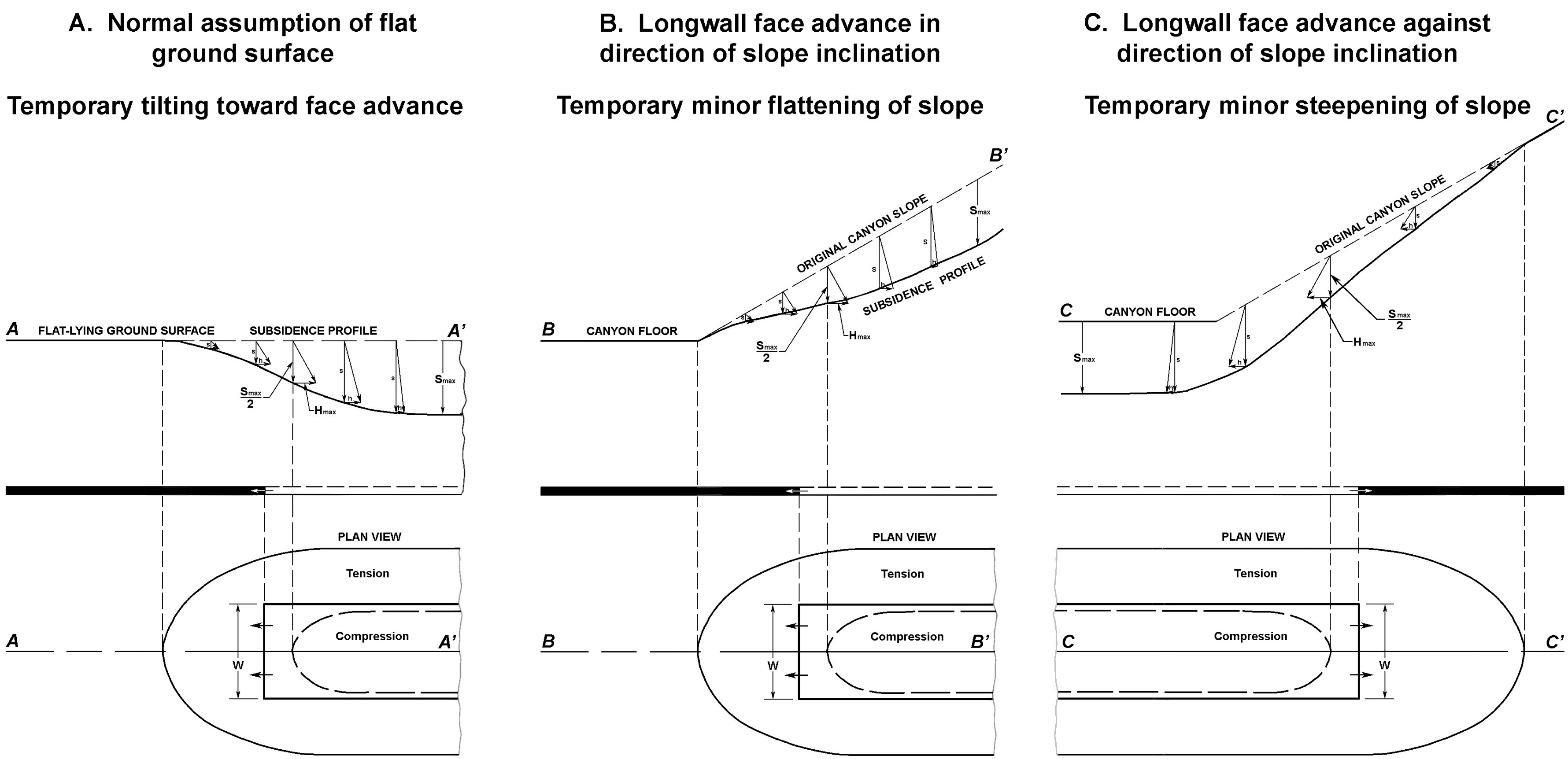

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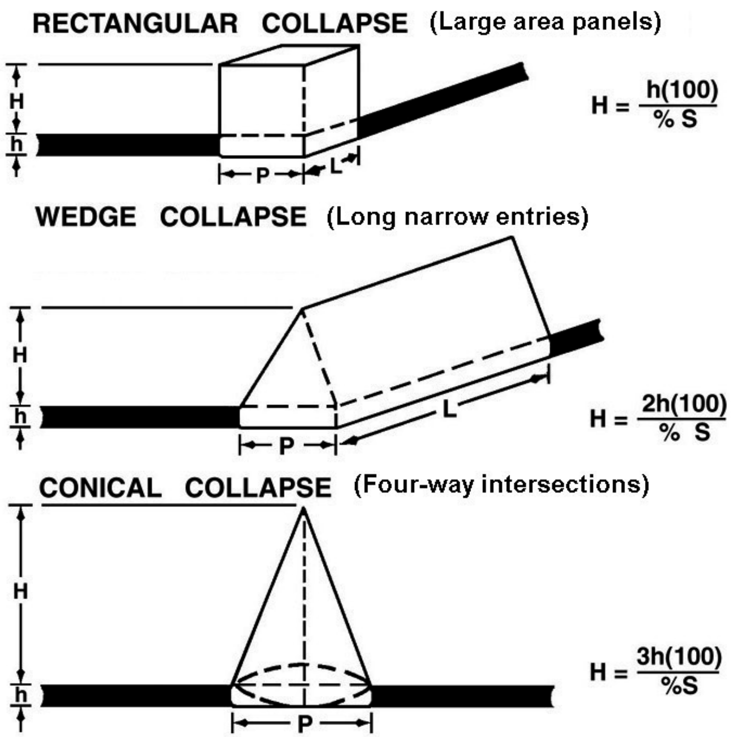
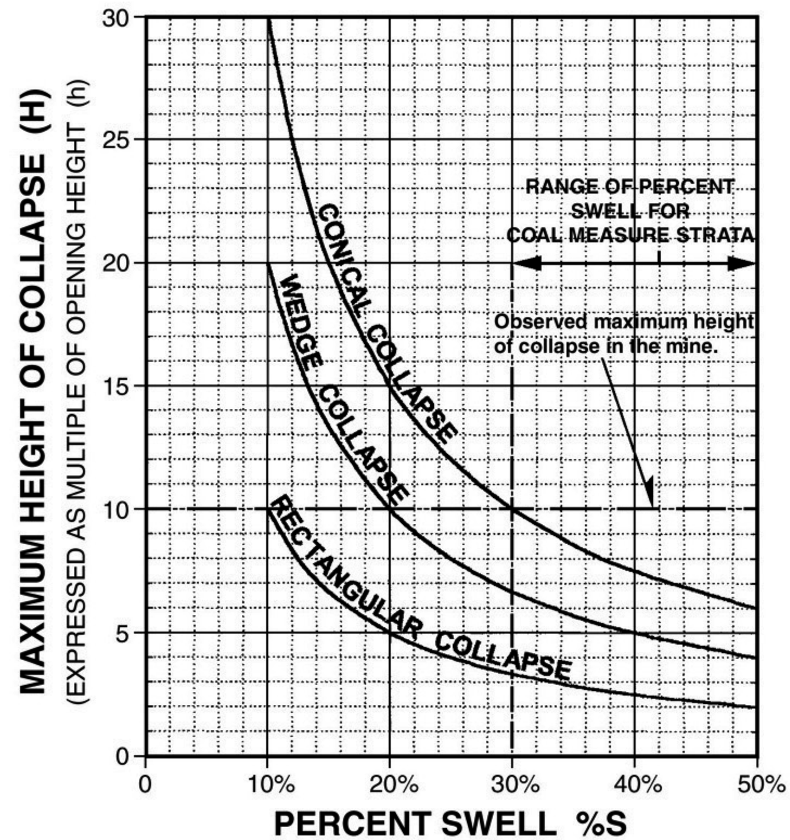
Figure 9
Localized Mining Induced Slope Angle Changes



$$\% S = \text{PERCENT SWELL} = \frac{Vc - Vo}{Vo}(100)$$

Vo = ORIGINAL VOLUME OF UNBROKEN ROOF STRATA
Vc = VOLUME OF COLLAPSED ROOF STRATA

Diagram showing notation for calculating maximum height of collapse (H) in relation to geometry of collapse.



Graph showing variation in maximum height of collapse for different modes of failure and percent swell of rock.

(modified from Piggott & Eynon, 1977)

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Figure 10
Potential Collapse Heights Above Different Mine Opening Geometries

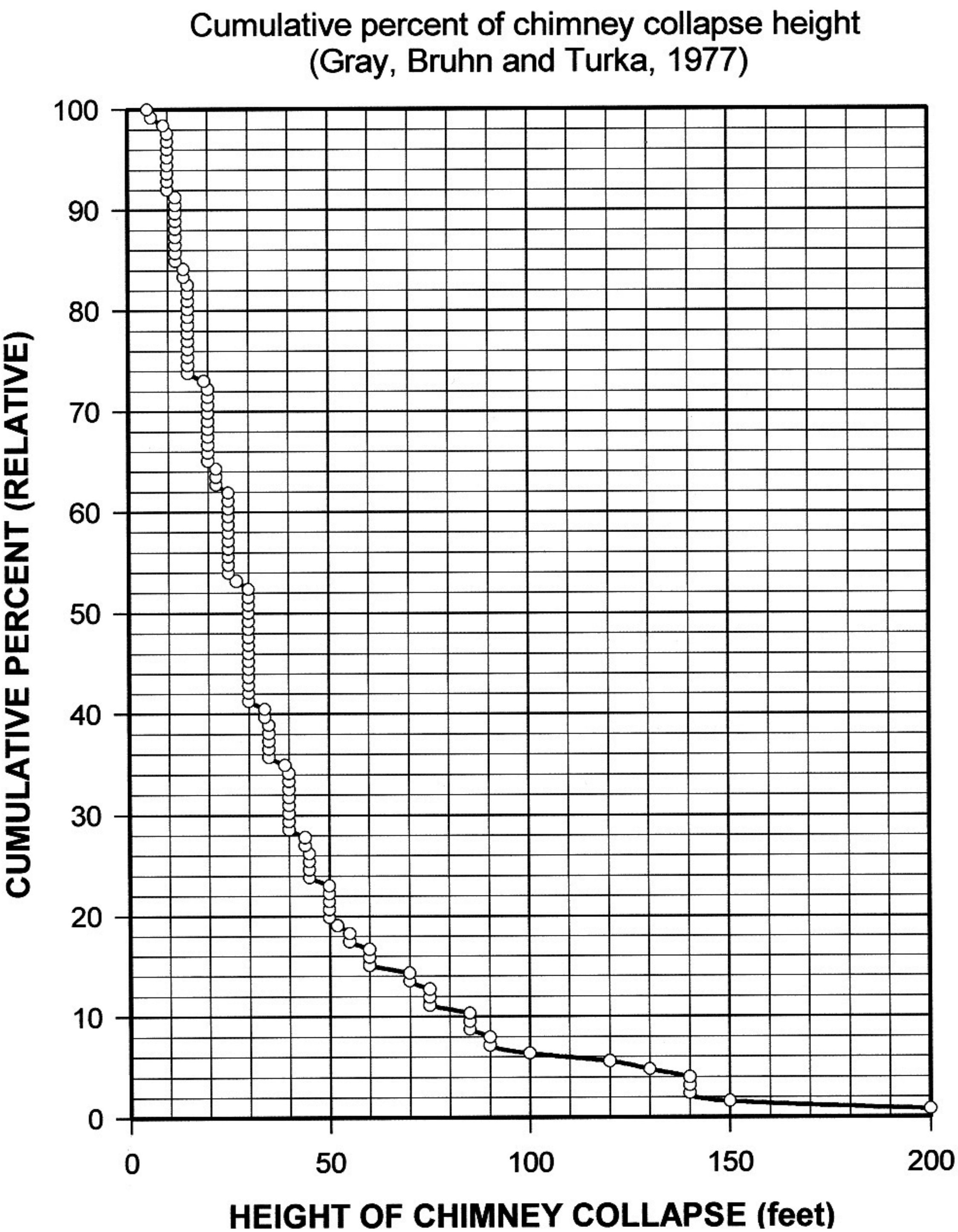

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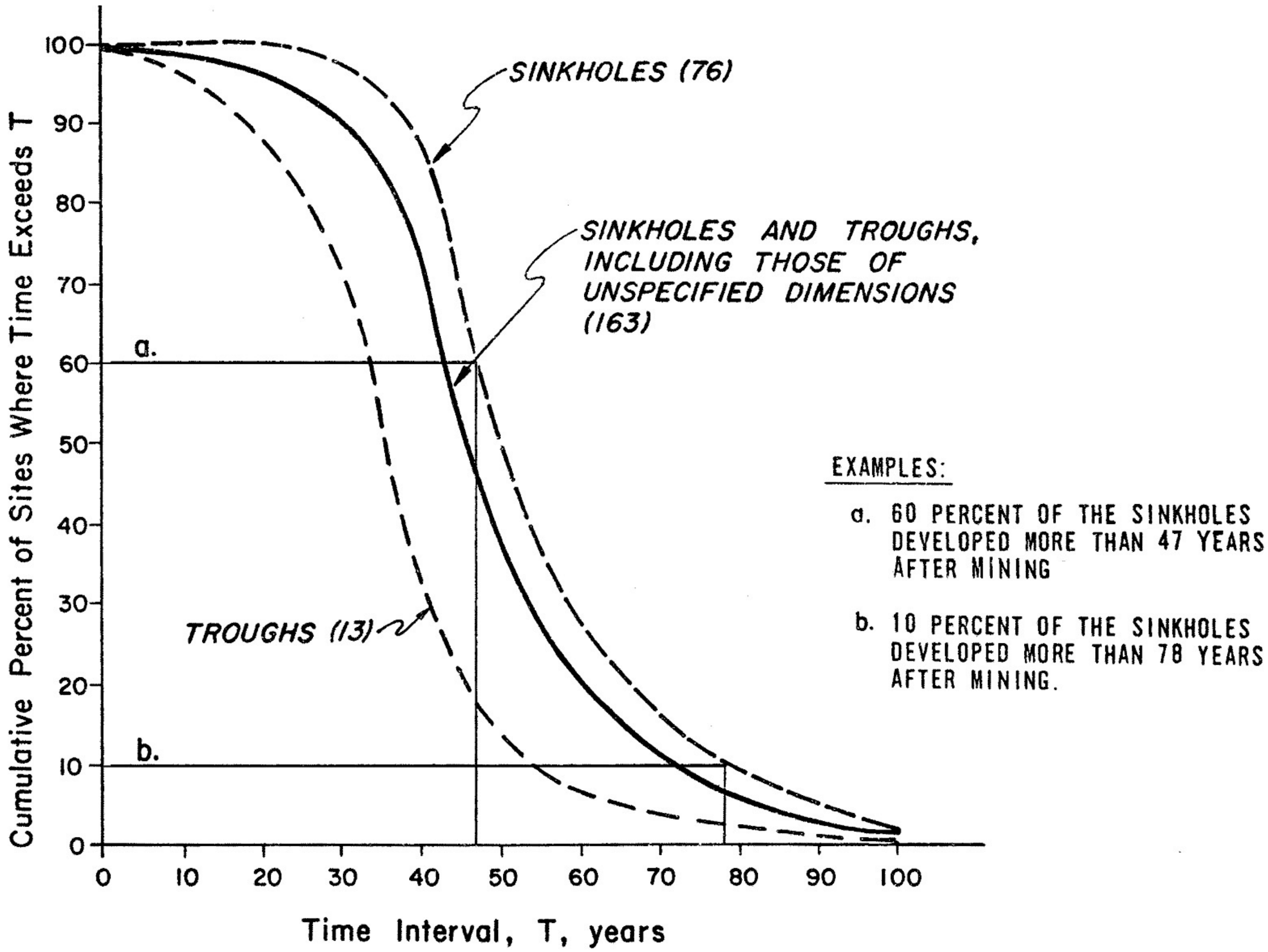
Figure 11
Cumulative Percent of
Chimney Collapse Height



Source: Gray, Bruhn & Turka, 1977

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Figure 12
Time Interval Between Mining and Surface Breached or Dropped

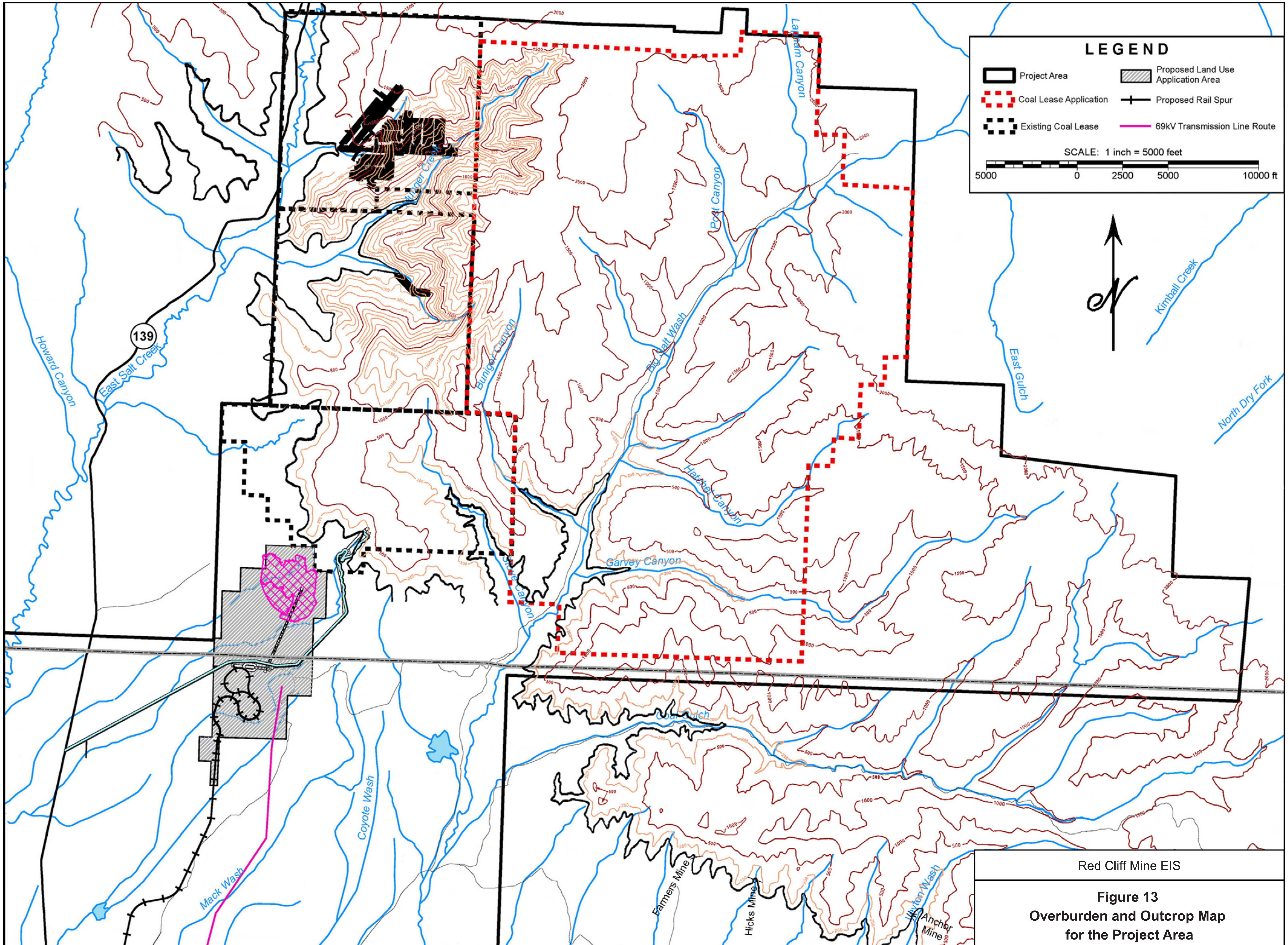

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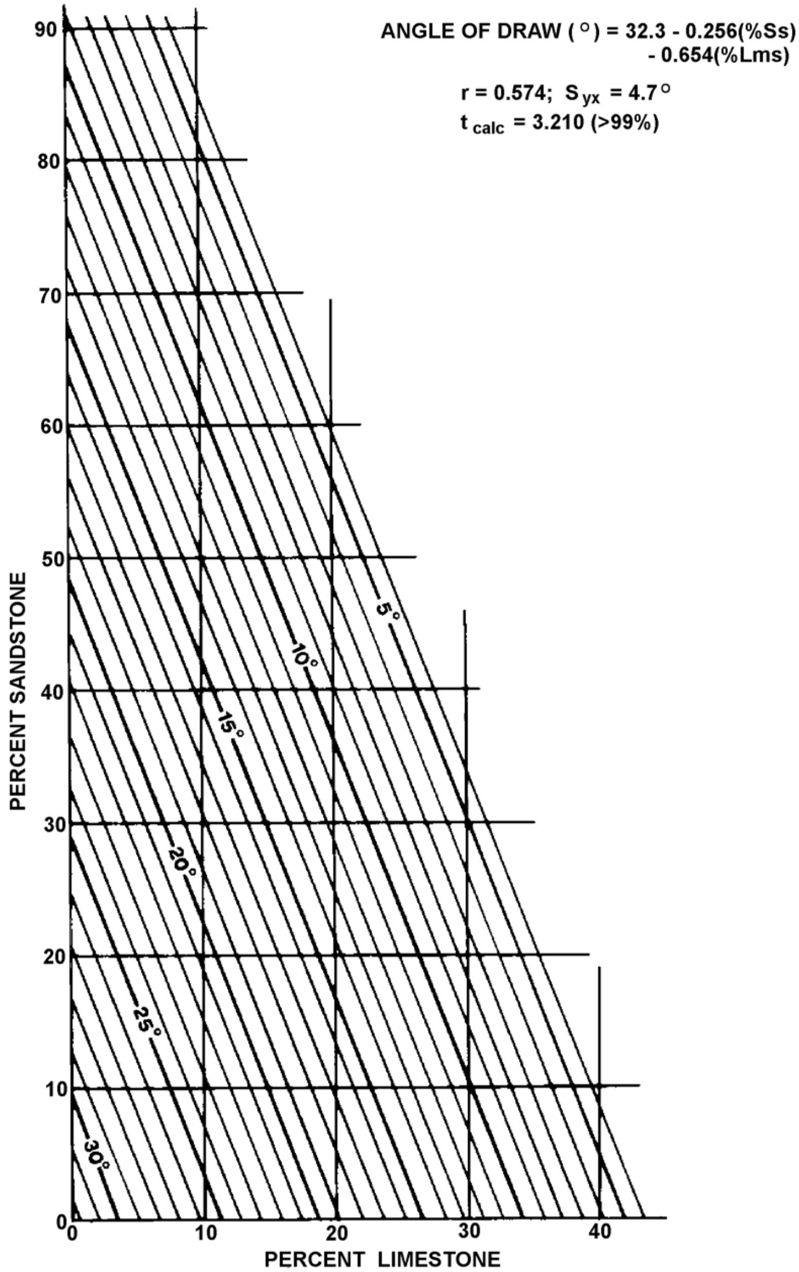
Figure 13
Overburden and Outcrop Map for the Project Area



Estimated Angle of Draw in Relation to Percent Sandstone and Limestone (Abel & Lee, 1984)

Red Cliff Mine EIS

Figure 14
Estimated Angle of Draw in Relation to Percent Sandstone and Limestone

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Figure 15
Cross Panel Compression Ridge in Alluvium, York Canyon Mine

Red Cliff Mine EIS

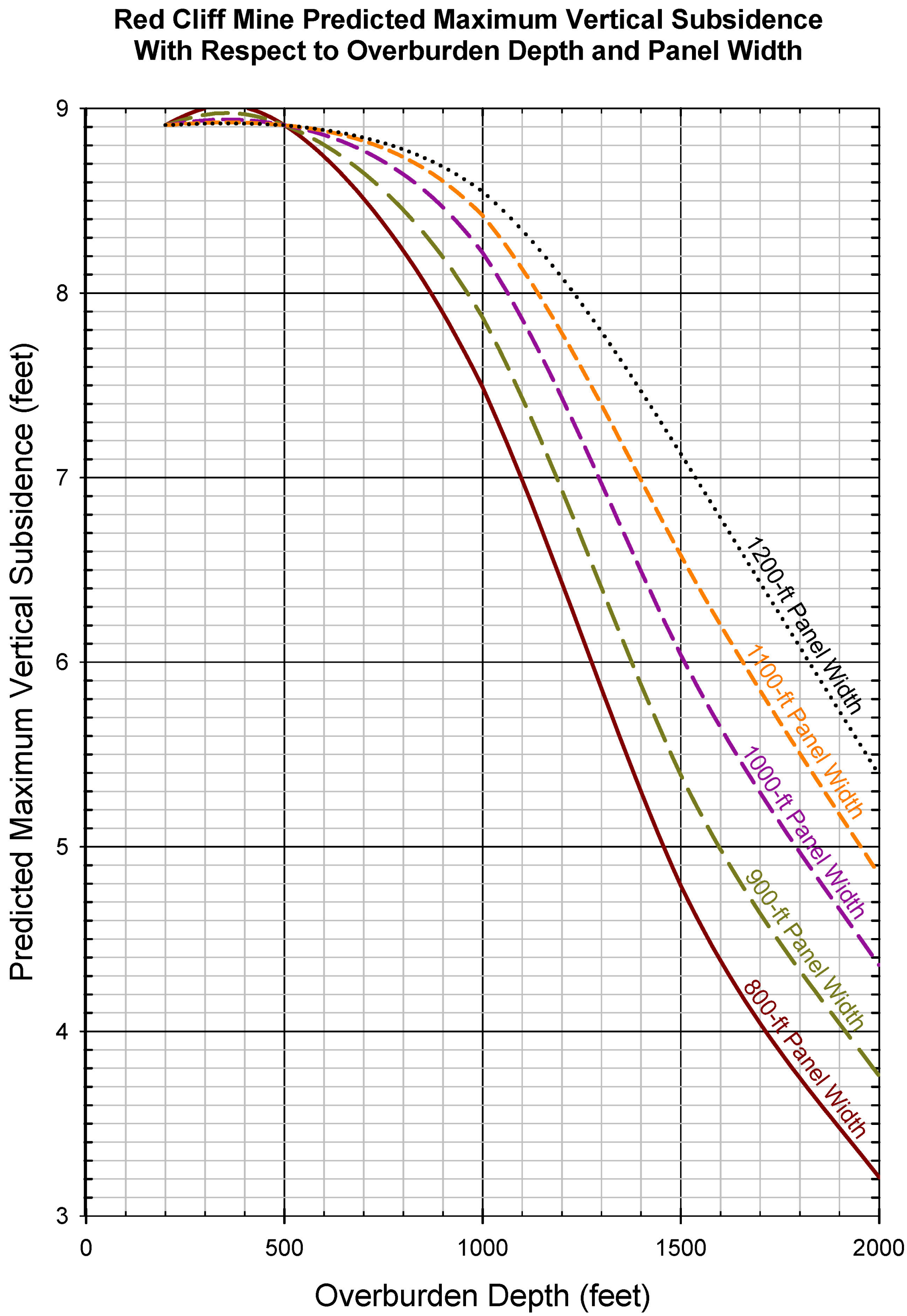
Figure 16
Cross Panel Tension Cracks in Alluvium, York Canyon Mine

Red Cliff Mine EIS

Figure 17
Ribside Tension Crack on Steep Slope
York Canyon Mine

Red Cliff Mine EIS

Figure 18
Ribside Tension Cracks in Road Fill and Cliff Face, York Canyon Mine



Red Cliff Mine EIS

Figure 19
Maximum Vertical Subsidence (S_{max}) with Respect to Panel Width and Depth

Red Cliff Mine EIS

Figure 20
Tension Crack Over Starter Room, York Canyon Mine

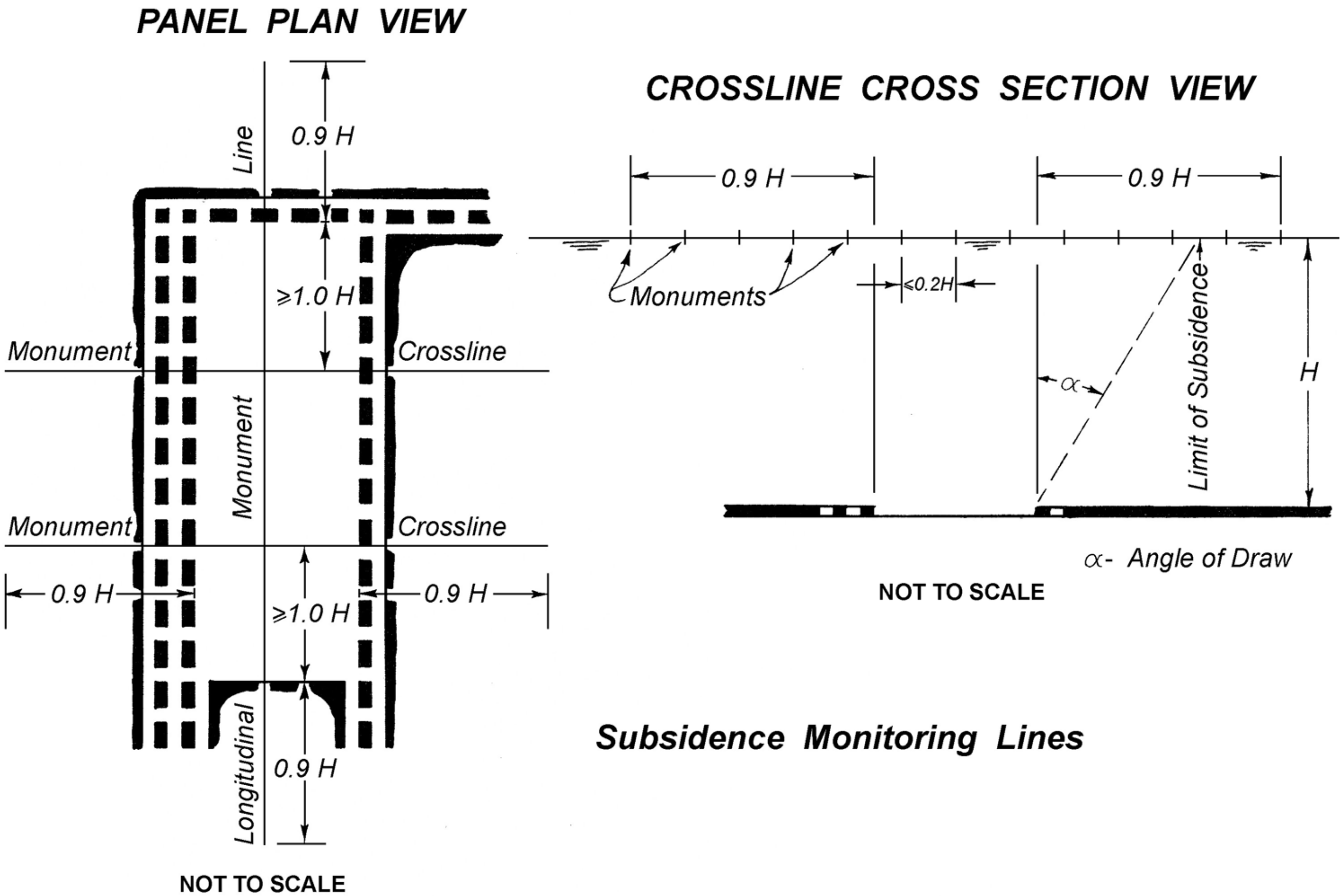


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Figure 21
Subsidence Monitoring Program

APPENDIX A. RECOMMENDED LIMITS FOR SUBSIDENCE INDUCED STRAIN AND TILT

Table A1. Acceptable Subsidence Damage

References: (1) Wagner & Salamon, 1973; (2) Voight & Pariseau, 1970

Horizontal Strain $(\mu\varepsilon)$	Vertical Strain $(\mu\varepsilon)$	Tilt Tan	Tilt (α)	Comments and References
1000	1000	0.0010	0.057°	"tolerable level of strain likely to be on the order of"---for high speed hoisting (1)
500-1000	500-1000			High continuous brick walls damaged (2)
1000-2000	1000-2000			One-story brick mill building, wall cracking (2)
1000	1000			Plaster cracking (qypsum) (2)
2500-4000	2500-4000			Reinforced-concrete building frame damaged (2)
3000	3000			Reinforced concrete curtain walls cracked (2)
5000	5000			Steel frame, continuous simple steel frame distorted (2)
		0.004	0.229°	Tilting limits for smoke stacks and towers (2)
		0.010	0.573°	Rolling of trucks stacking goods (2)
Machine operation limits:		0.003	0.172°	Cotton loom (2)
		0.0002	0.011°	Turbo-generator (2)
		0.003	0.172°	Crane rails (2)
		0.01 to 0.02	0.573° to 1.146°	Floor drainage problems (2)

Table A2. Categories of Protection, Poland
(Brauner, 1973)

Category	Allowable tilt	Allowable strain	Explanation
I	0.0025 (0.143^o)	$1500\mu\varepsilon$	Slight damage allowable, such as hair hair cracks in plaster.
II	0.0050 (0.286^o)	$3000\mu\varepsilon$	Small reparable damage allowable.
III	0.0100 (0.573^o)	$6000\mu\varepsilon$	Building damage severe, but does not does not destroy the building or impair its service.
IV	0.0150 (0.859^o)	$9000\mu\varepsilon$	Movements so severe that reinforced structures are required to resist them.

Table A3. Tolerance of Structures to Differential Subsidence
(Hutchings, et al,1978)

DIFFERENTIAL SUBSIDENCE (Strain - %)	STRUCTURAL SIGNIFICANCE
0.1% ($1000\mu\varepsilon$)	Limiting value for high continuous brick walls and brick-clad column frames
0.1%-0.2% ($1000-2000\mu\varepsilon$)	Single story brick mill building, wall cracking
0.2%-0.4% ($2000-4000\mu\varepsilon$)	Limiting value for steel and reinforced concrete frames
0.7% ($7000\mu\varepsilon$)	Structural damage to buildings
0.8% ($8000\mu\varepsilon$)	Slight damage to 2-1/2 story brick veneer homes
2% ($20000\mu\varepsilon$)	Severe damage to 2-1/2 story brick veneer

Table A4. Subsidence Damage Description for Horizontal Strain
(British National Coal Board, 1975)

Class of damage	Change of length of structure	Description of typical damage
Very slight or negligible Example: 50-ft long building extended	Up to 0.1 ft	Hair cracks in plaster. Perhaps isolated slight fracture in the building, not visible on outside. 50 u - in./in.
Slight Example: 110-ft long building extended	0.1 ft-0.2 ft	Several slight fractures showing inside the building. Doors and windows may stick slightly. Repairs to decoration probably necessary. 1,600 u - in./in.
Appreciable Example: 90 ft long building extended	0.2 ft-0.4 ft	Slight fractures showing on outside of building (or one main fracture). Doors and windows sticking ; service pipes may fracture. 3,700 u - in./in.
Severe Example: 220 ft 1ong apartment house compressed	0.4 ft-0.6 ft	Service pipes disrupted. Open fractures requiring rebonding and allowing weather into the structure. Window and door frames distorted; floors sloping noticeably. Some loss of bearing in I-beams. If compressive damage, overlapping of roof joints and lifting of brickwork with open horizontal fractures. 2,300 u - in./in.
Very severe Example: 180 ft long apartment	More than 0.6 ft	As above, but worse, and requiring partial or complete rebuilding. Roof and floor beams lose bearing and walls lean badly and need shoring up. Windows broken with distortion. Severe slopes on floors. If compressive damage, severe buckling and bulging of the roofs and walls. 6,000 u - in./in.

Table A4. Subsidence Damage Description for Horizontal Strain (Cont.)

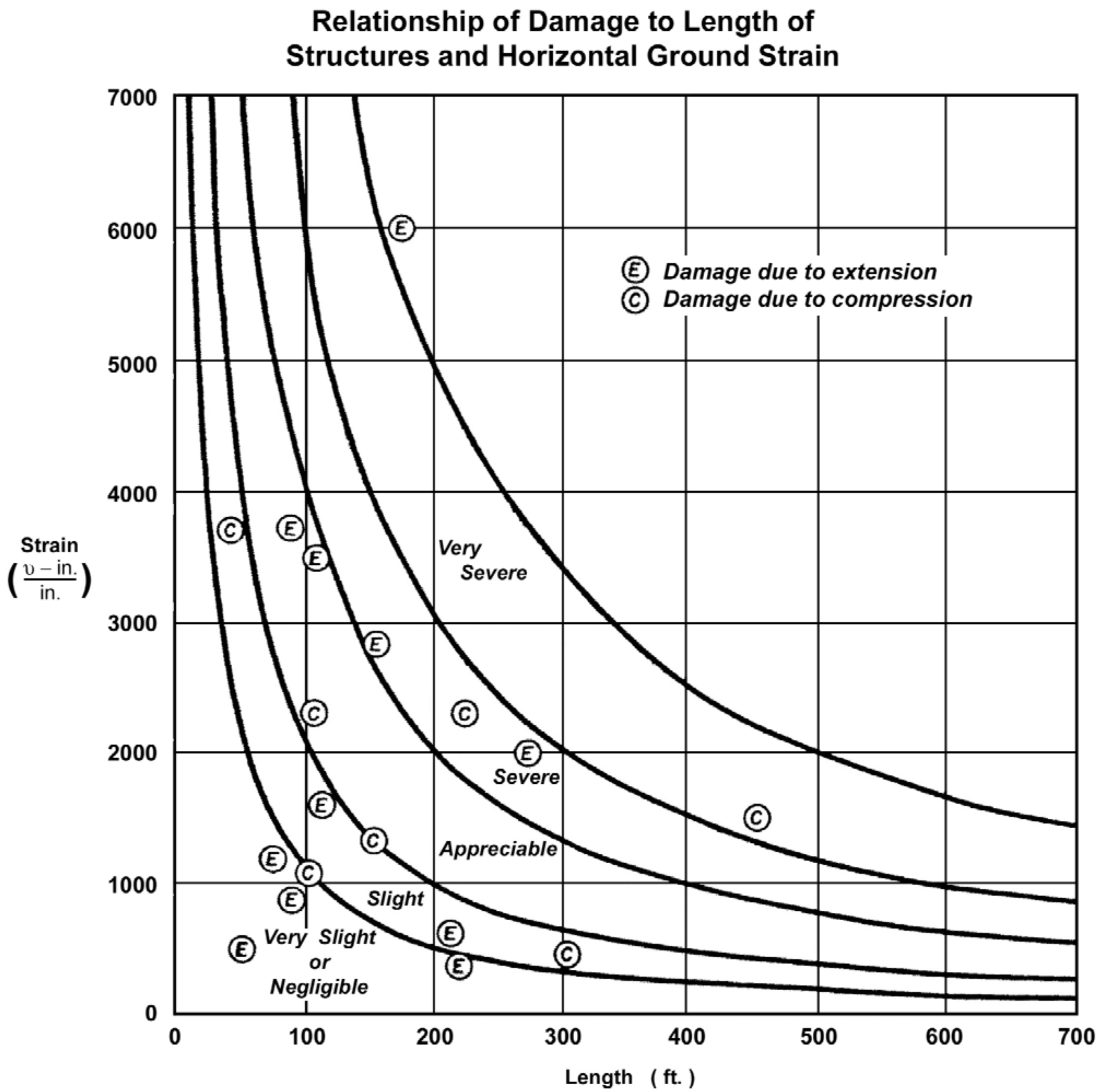

Table A5. Classication of Permissible Strain and Tilt (Ochab, 1961)

POLISH MINISTRY FOR MINING AND POWER

PERMISSIBLE HORIZONTAL STRAIN	PERMISSIBLE TILT (°)	TYPE OF STRUCTURE OR SERVICE
0.2% (2000 $\mu\varepsilon$)	0.142°	Gas mains which require particular protection against the danger of a gas explosion if damaged, also items such as water tanks and industrial installations recognized as being especially important or particularly susceptible to damage with regard to life and safety
0.4% (4000 $\mu\varepsilon$)	0.283°	Industrial reinforced concrete buildings of monolithic construction or with gantry cranes, churches with domes and other big buildings for public use such as hospitals, theaters, etc, river beds and water reservoirs, provided the hydro-geological opinion is that the character of the ground does not require any increase or decrease of safety conditions, main railway lines and railway stations with a quantity of technical equipment, tunnels and arched bridges, main water pipes, also large residential buildings with a length of more than 20 m
0.6% (6000 $\mu\varepsilon$)	0.567°	Main roads, railway tracks and small railway stations, girder bridges, industrial buildings of brick, steel and timber construction without cranes and which are not too susceptible to ground movements, cooling towers, high chimney stacks, water towers, churches with beam construction roofs, residential buildings with a length of 10 to 20 m, residential buildings more than 20 m long, but of a specially protected construction, main sewers and airfields
0.9% (9000 $\mu\varepsilon$)	0.858°	Large sports stadiums, residential buildings up 10 m long, residential buildings 10 to 20 m long buildings of a specially protected construction and other items of small importance