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# IMPLICATION OF HIGHLY ANISOTROPIC HORIZONTAL STRESSES ON ENTRY STABILITY AT THE WEST ELK MINE, SOMERSET, COLORADO

J.F.T. Agapito, Principal and Leo J. Gilbride, Principal
Agapito Associates, Inc.
Grand Junction, CO, USA

Wendell A. Koontz, Chief Geologist
Ark Land Company
Somerset, CO, USA

## ABSTRACT

Overcore measurements at the North Fork Valley (NFV) coal mines in western Colorado have shown that horizontal stresses are highly anisotropic. Measurements have been made in four mines at various depths. In many measurements, the maximum horizontal stress is three to four times higher than the minor horizontal stress. At the West Elk Mine, maximum and minimum horizontal stresses of 24 MPa and 6 MPa, respectively, have been measured at depths of 640 meters (m).

Under highly anisotropic stress conditions, ground control problems associated with both high and low horizontal stresses can develop. While high horizontal stresses can produce cutter failures and floor heave, low horizontal stresses can allow block fallouts.

This paper summarizes the horizontal stress measurements in NFV mines and, in particular, in the West Elk Mine where their role in roof fall and floor heave failures is discussed. This experience has led to an improved use of ground support and safer mining operations at depths of 640 to 700 m.


Figure 1. Location of North Fork Valley

## INTRODUCTION

Coal has been mined in the NFV mines (Somerset Coal Field) for over a century. The NFV is located in western Colorado, about 175 km from Grand Junction, Colorado (Figure 1). Historical production has been from small room-and-pillar mines. About 20 years ago, modern longwall mining was introduced, allowing the extraction of high tonnages from efficient, large mining operations.

In situ stress determinations using the overcoring technique have been made in the new mines to provide base data for geotechnical design. Stress measurements can be difficult to make without an experienced crew. Although they can be time consuming and expensive, the measurements often more than justify the effort and cost. The data obtained from the NFV mines have been very useful not only for evaluating the mine design, but also for a better understanding of ground behavior. Ultimately, the stress measurement results have provided valuable input for mine design and ground support changes made to reduce ground control problems.

This paper presents first an overview of the geology as the background to a complex stress environment where sedimentary and mountain building forces commingle. Maximum and minimum horizontal stresses from four mines are then summarized, followed by a more detailed description of stress at a deep site of the West Elk Mine (Mountain Coal Company). The objective is to show the existence of strong anisotropy and a marked increase in the magnitude of horizontal stresses at the deeper site. Ground control problems associated with both high- and low-horizontal stresses can adversely impact operations. A large floor bump and roof falls experienced at the West Elk Mine are discussed and linked to the stress environment. Finally, changes in operational procedures and ground support leading to a more efficient and safer mining operation are described.

## COMPLEX GEOLOGIC ENVIRONMENT

The NFV mines are located in the southern rim of the Piceance Creek Basin. The valley is surrounded by uplifted lands; to the south, north, and west, the Gunnison, White River, and Uncompahgre uplifts, respectively, and to the east, the Elk Mountains. The coal-bearing strata belong to the Mesa Verde Formation of the Cretaceous Period. During deposition, transgressions and regressions of the seashore across the region caused repeated grading of sandstones, shales, mudstones, and coal. Most of the sandstones thicken, thin, and pinch out over short, lateral distances. Figure 2 shows a typical stratigraphic section. Coal has been mined from five coal seams (Seams B, C, D, E, and F) within a stratigraphic interval 150 to 180 m thick near the base of the Mesa Verde Formation. A thick, very strong sandstone, the Rollins Sandstone, underlines the coal beds and forms the base of the Mesa Verde Formation. The Mancos Shale underlies this thick sandstone.

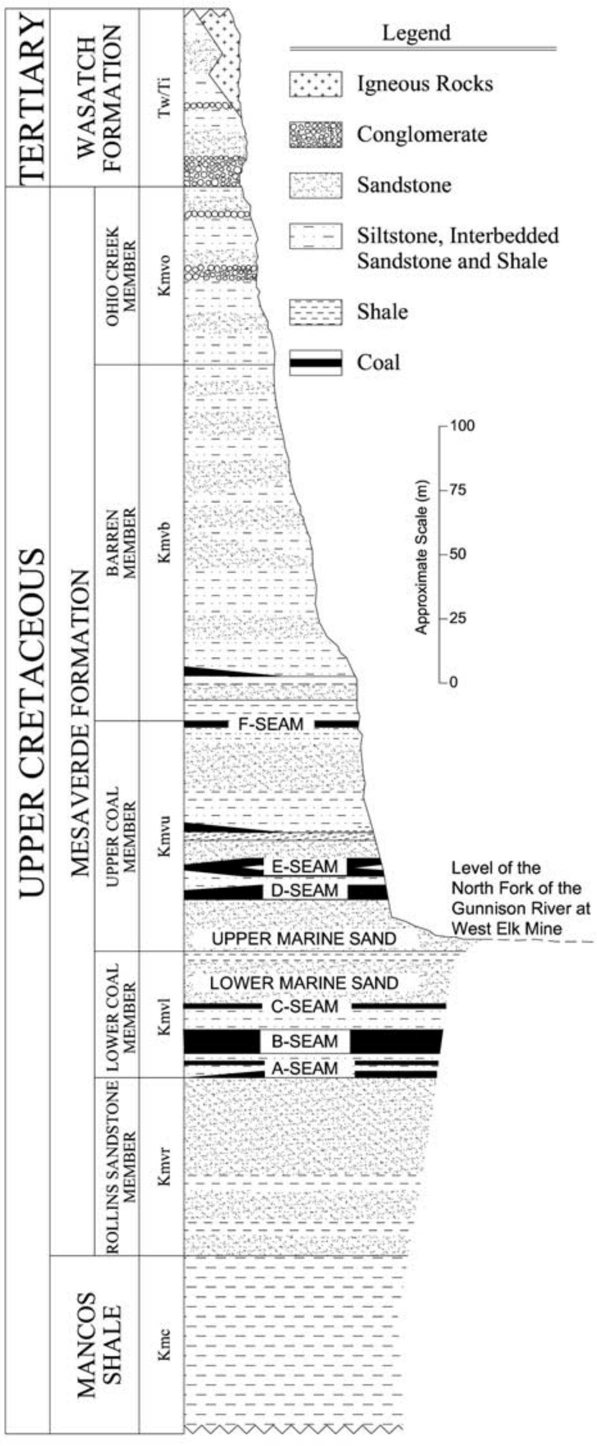

Figure 2. General Stratigraphy of District

A rugged and incised topography makes the overburden depth highly variable. It can range from 0 m at coal outcrops to 760 m in relatively short distances beneath ridges. Figure 3 shows a generalized view of the mining district. The strata tend to dip to the northwest at gentle angles of 3° to 5°. The coal face cleat has a dominant N60°E trend and is very pronounced.

Of the numerous distinct fault types present in the NFV, it is the steeply dipping, normal faults which trend in a northwest, northeast, east-west, and north direction that pose the significant challenges. These normal faults show offsets of less than 1 m to 7 m or more. At the West Elk Mine, the normal faults strike to the northeast and dip steeply (>70°) to the northwest. They show small lateral (extentional) offsets and vertical downthrows of a few centimeters to 6 m. In many locations of the mine steep, strike-slip faults occur in association with the normal faults, suggesting that they were formed from a (stress/strain) transfer movement from the normal faults. They strike at an angle of about 60° to the normal faults. The faults have little or no surface expression, suggesting that they were formed at depth probably due to emplacement of igneous rocks beneath the mine. Overcore measurements, discussed in the next section, indicated that the strike-slip faults are parallel to maximum horizontal stress (*P*).

## HORIZONTAL STRESSES

Stress determinations have been made in the immediate roof of some of the mines using the overcoring technique and the United States Bureau of Mines (USBM) borehole deformation gage (BDG). The horizontal, secondary principal stresses were obtained by overcore holes drilled perpendicularly into the roof. Table 1 summarizes the stress data, and Figure 4 shows the stress ellipses from seven NFV sites.

*P* shows a consistent trend averaging N81°E and a *P/low stress component (Q)* ratio average of 3.7, indicating strong anisotropy.

Measurements made in horizontal overcore holes in some of the sites have shown that the vertical stresses are close to the calculated vertical stresses when a 0.025 MPa/m gradient is used. Figure 5 relates *P* to depth and to vertical stresses based on a 0.025 MPa/m gradient. Most of the measurements are close to the gradient line indicating moderate values with close agreement between *P* and vertical stresses. In the shallower and deeper sites, however, *P* is significantly higher than the vertical stresses. In the deeper site (West Elk) the magnitude of *P* is higher at about one and a half times the vertical stress. The horizontal stress gradient in this area increased at a much higher rate than the vertical gradient (Sites 6 and 7, Table 1).

Figure 6 shows the stress profile in the roof at the deeper, 640-m site. The measurements were taken in a gateroad 10 months before longwall mining. The profile shows first a low *P* of 14 MPa at 1 m above the roof, increasing to 24 MPa at 2.6 m, and then decreasing to 19 MPa at 7 m away from the influence of the opening. Stresses can be visualized as a flow, concentrating 2.6 m above the roof, forming an arch above a distressed, relaxation zone in the immediate roof. Much less variation and lower magnitudes are observed in *Q*. A *P/Q* ratio of 4.4 was obtained indicating a strong anisotropy.

Figure 7 shows the site location. *P* is nearly parallel with the previously discussed strike-slip faults. A magnetic field survey in

Figure 3. Typical Topography of the North Fork Valley Mining District

**Table 1. Summary of Horizontal Stress Determinations—North Fork Valley Mines**

| Site | Mine | Coal Seam | Cover Depth (m) | Maximum Horizontal Stress (*P*) (MPa) | Minimum Horizontal Stress (*Q*) (MPa) | Orientation of *P* | *P/Q* Ratio |
|---|---|---|---|---|---|---|---|
| 1 | Orchard Valley—Bowie Resources, Ltd. [1] | B | 107 | 8.0 | 1.9 | N69°E | 4.2 |
| 2 | Orchard Valley—Bowie Resources, Ltd. [1] | B | 496 | 12.2 | 4.2 | N83°W | 2.9 |
| 3 | Bear—Bear Coal Co. [2] | B | 381 | 9.8 | 2.3 | N69°E | 4.3 |
| 4 | Bear—Bear Coal Co. [2] | C | 274 | 4.5 | 1.9 | N82°W | 2.4 |
| 5 | Bowie No. 2—Bowie Resources, Ltd. [3] | D | 305 | 9.2 | 1.7 | N85°E | 5.4 |
| 6 | West Elk—ARCO Coal Co. [4] | B | 320 | 11.9 | 5.8 | N67°E | 2.1 |
| 7 | West Elk—Mountain Coal Co. [5] | B | 640 | 24.2 | 5.5 | N78°E | 4.4 |
| | | | | | **Average** | **N81°E** | **3.7** |

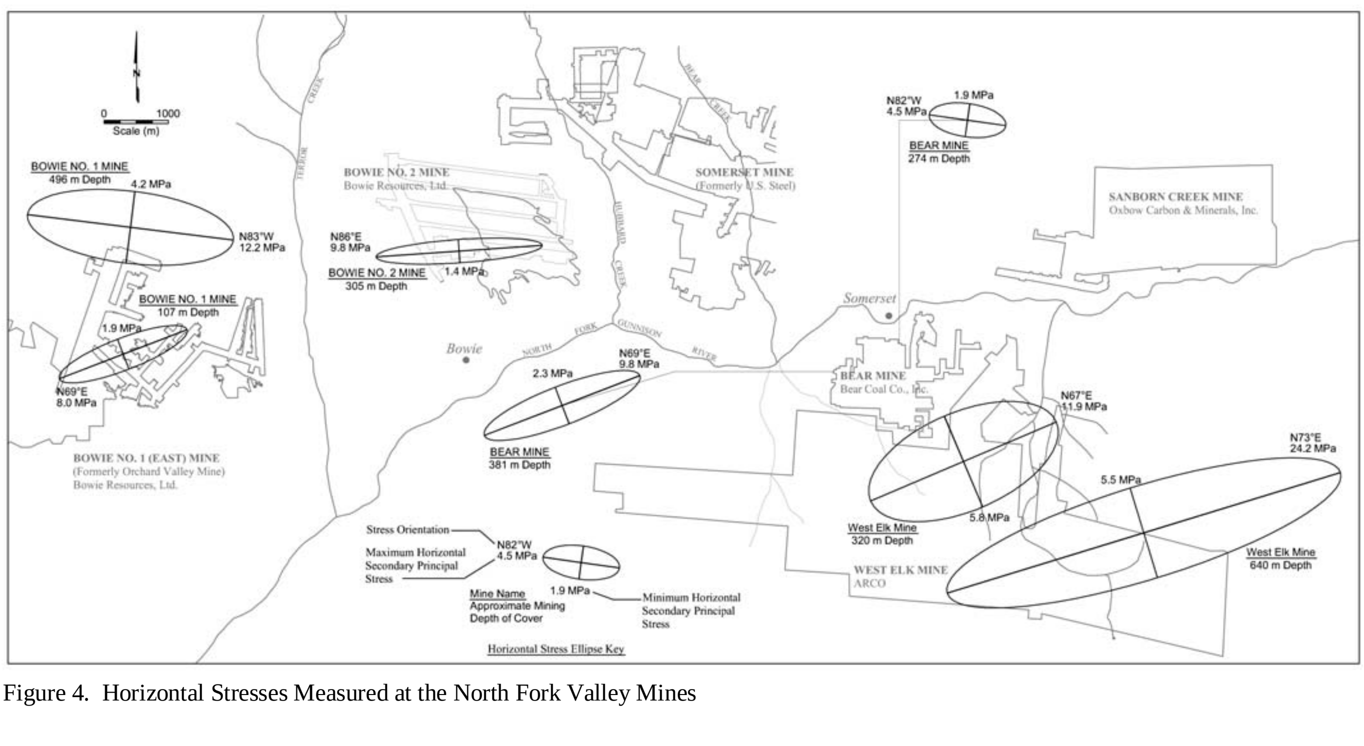


Figure 4. Horizontal Stresses Measured at the North Fork Valley Mines

the area of West Elk Mine showed anomalies interpreted as a large laccolithic intrusion at a depth of 2,135 m [6]. This intrusion could be partly responsible for the current stress field and some of the normal faults with little or no surface expression.

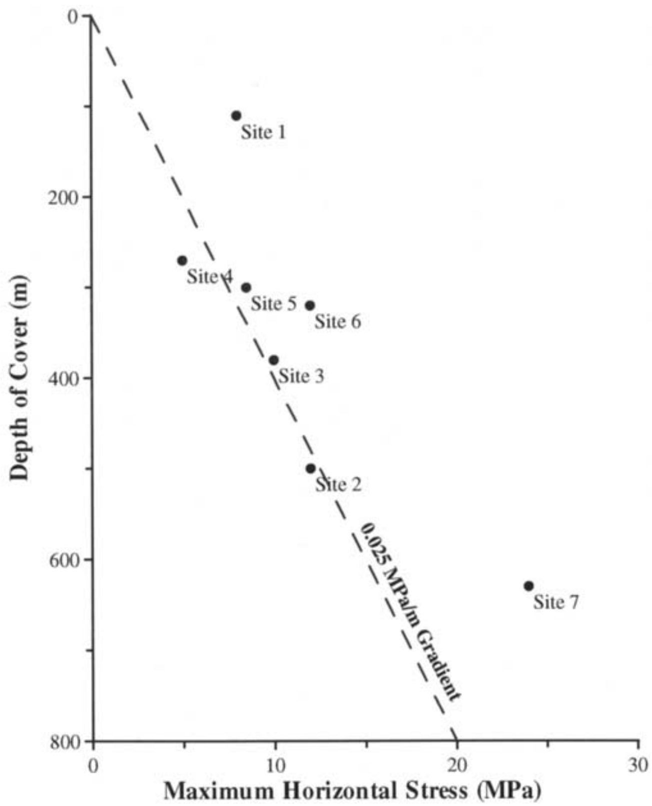


Figure 5. Relationship Between *P* and Depth

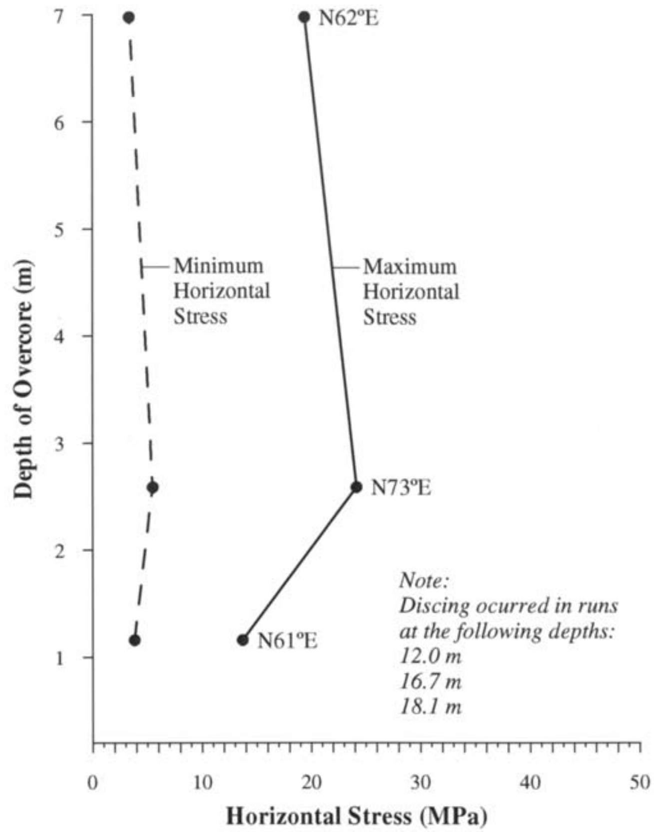


Figure 6. Horizontal Roof Stress Profile, Site 7

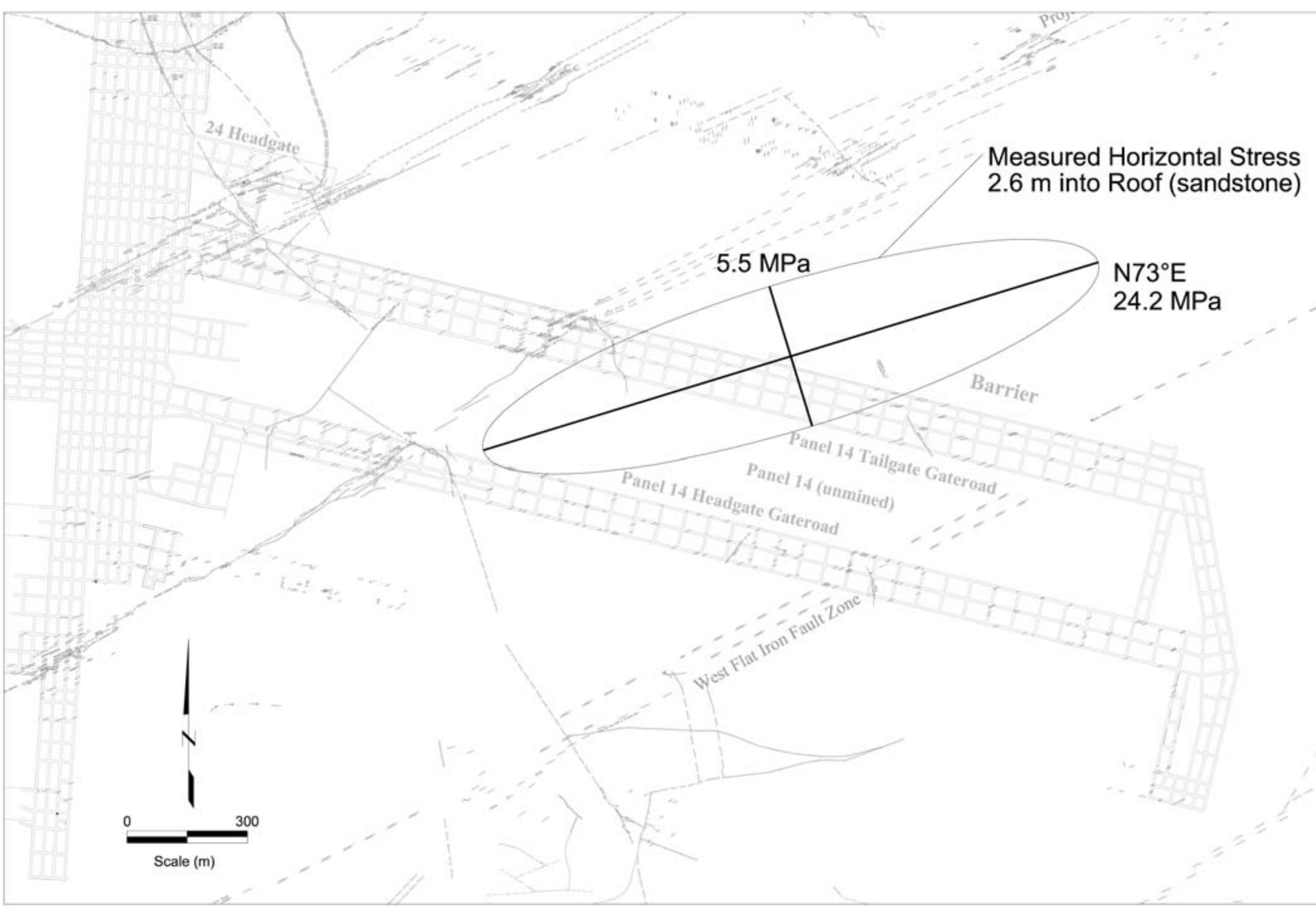


Figure 7. Faulting and Horizontal Stress Orientation, Site 7

Figure 8a. Crushing of Roof Beds due to High Horizontal Stress—Bent Bolt Indicates Attitude of Shearing

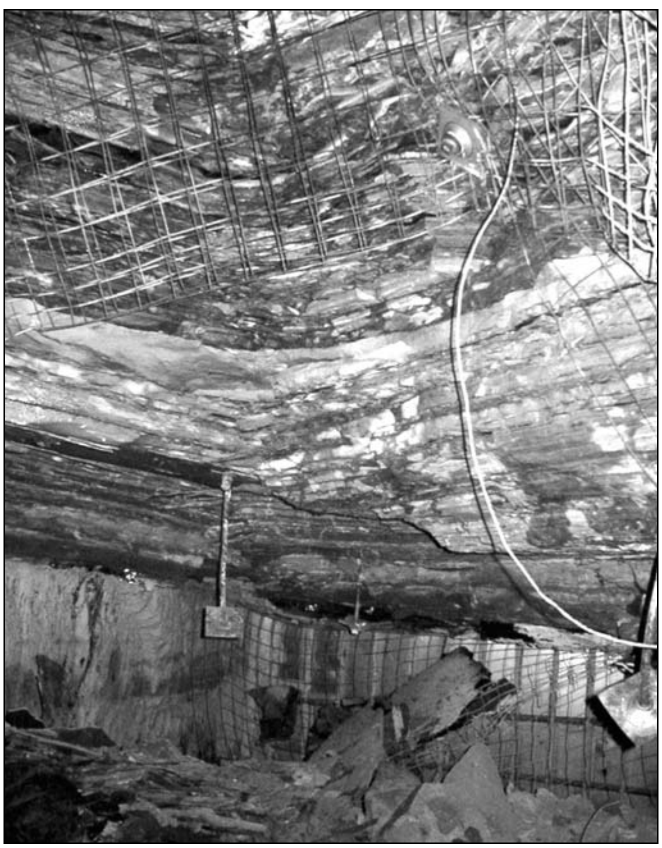

Figure 8b. Horizontal Stress Damage in the Roof—Roof Fall Following Crushed Zone

Figure 9. Horizontal Stress Damage Along Corner of Roof

Figure 10. Open (15 cm) Aperture along Fault Blade in Roof in Low Horizontal Stress Zone

## ROLE OF HORIZONTAL STRESSES IN GROUND PROBLEMS

Ground problems are seldom caused by a single factor, but by a combination of factors in which geology and stresses play a key role. At West Elk Mine, highly anisotropic, horizontal stresses have caused a considerable number of roof falls and floor heave failures.

The effect of high-horizontal stresses is often expressed in the roof by compressional/shear failures, which sometimes occur at or near mid-spans with the roof beds crushing down into the entries (Figure 8). Other times, failure comprises "cutters" as illustrated in Figure 9. In low horizontal stress regimes, rock blocks can fall out much easier than in a high-stress environment, particularly where natural open apertures exist along fault blades (Figure 10).

A characteristic roof fall pattern at West Elk Mine consists of falls, some as high as 3 m or more, with the long axis perpendicularly to *P* and the strike-slip faults as illustrated in Figure 11. Floor heave usually also develops roughly parallel to the fall. This failure behavior is linked to the horizontal stresses.

Small to moderate amounts of floor heave (1/4 to 1/3 m) are common through the mine and sometimes occur soon after development. The heave tends to increase with time and longwall mining. When needed, it is removed by grading the floor.

A large floor bump occurred in the Panel 14 Tailgate on November 5, 2001, not far from the overcore site where stresses had been measured prior to longwall mining. Figure 12 shows the face position at the time of the event, floor bump location, overcore location with *P* and *Q*, and major fault zones. The bump registered as a 3.4 Richter scale event at the Golden, Colorado, United States Geological Survey (USGS) seismic station about 330 km to the east. It occurred at a depth of 500 to 600 m, less than 30 m from a normal fault zone.

The amount of heave was as much as 2.5 m, completely closing the entries at some locations. A few cans used as secondary support were destroyed (Figure 13), but others remained nearly vertical exerting good roof support even though almost buried by floor heave (Figure 14).

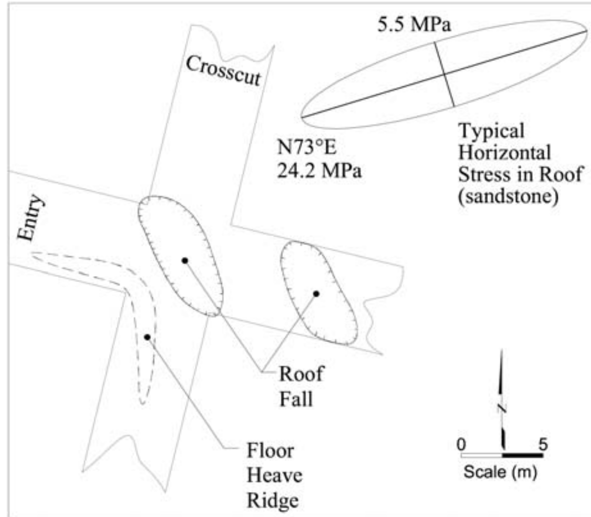


Figure 11. Roof Fall and Floor Heave Pattern

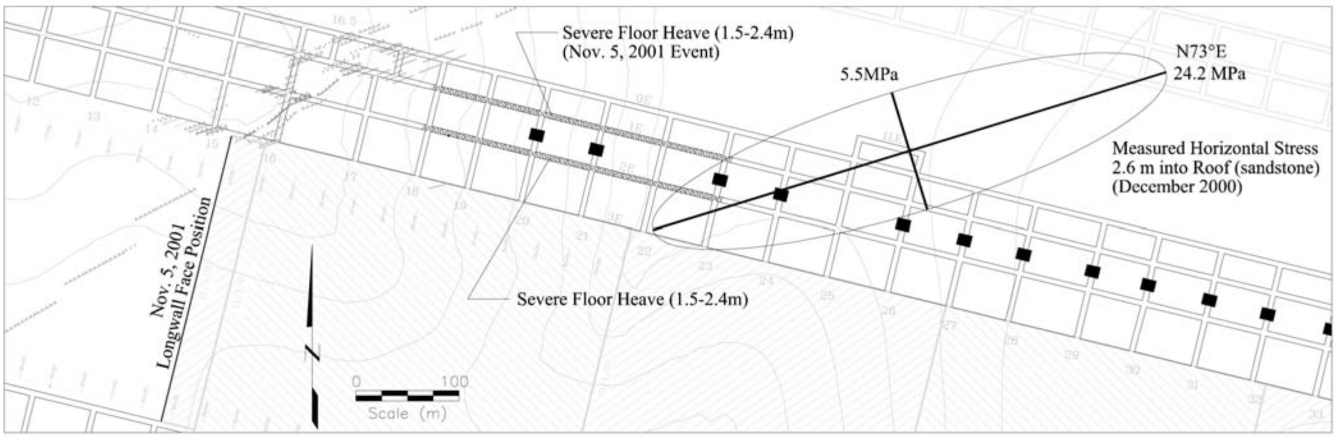


Figure 12. Floor Bump Location

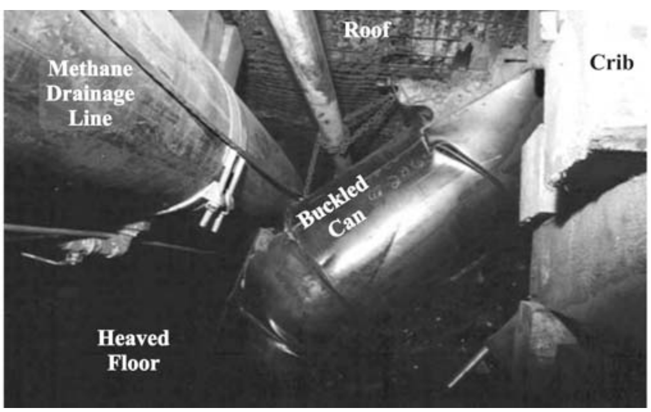


Figure 13. Buckled Can

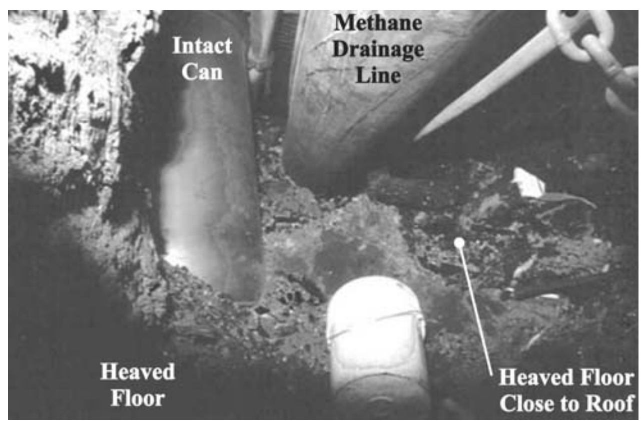


Figure 14. Floor Heave Around Can

The cause of this large bump can be attributed to existing horizontal stresses, deep and variable overburden, and the inconsistent transfer of vertical and horizontal stress across the fault structure. Experience at West Elk Mine has found that stress concentrations are evident in the gateroad developments at these faults. The effects are seen as rib spalling, additional floor heave, and “active” or “talking” roof and ribs as the stress equilibrates to the entry development.

## MITIGATING DIFFICULT GROUND CONDITIONS

In a complex, geologic environmental where gas and water have sometimes contributed to very difficult mining conditions, increased vertical loading caused by deeper cover, the horizontal stresses, and the non-uniform transfer of the stress have caused

West Elk Mine management to review and change operating and design procedures to mitigate ground control problems.

Heavier roof support has been adopted. A substantial increase in primary support was made by changing from Grade 60 rebar bolts to Grade 75 "Install III" full-resin bolts. These are installed at 1.5-m spacings. At depths of 350 m and beyond, the roof and ribs are reinforced with mesh and bolts in all beltways and travelways. In faulted areas where large blocks are susceptible to sliding out of the roof, carrier trusses at 1.5-m spacings or less are typically installed.

Cans (0.6- and 0.9-m diameter) and/or Cluster Props are routinely used for secondary support. Cans are installed in all tailgate entries on a two-row, staggered pattern at 3-m spacings, and in the middle entry during longwall retreat to provide an additional ventilation airway.

In planning the development through high-stress fault zones, the budgeted advance footage is decreased to account for decreased depths of cuts and increased roof support requirements. Typically, the budgeted footage is down-rated from 180 ft per unit shift (FPUS) to 120–150 FPUS.

Finally, panel orientation was reviewed. Two orientations have been used at the mine. First, in the earlier, shallower areas, panels were retreated in a north to south direction; and presently, in the deeper areas in an almost east to west direction (N80°W). A traditional rule of thumb, based on mines with high horizontal stresses, is that entries driven parallel to $P$ are less likely to have roof problems than entries driven perpendicular to $P$. Thus, better ground conditions may be achieved by maximizing the drivage parallel to $P$ and minimizing drivage perpendicular to $P$.

More recent work by Consol [7] and the USBM [8] indicates that optimum panel orientation occurs when $P$ is 20° from the gateroad alignment and the headgate is in the horizontal stress shadow of the gob. Based on these findings, the present panel orientation at the West Elk Mine seems close to the optimum orientation.

## CONCLUSIONS

Stress measurements in the immediate roof of the NFV mines show that in situ horizontal stresses are highly anisotropic with $P>3.7Q$ on the average and that the direction of $P$ is quite consistent, averaging N81°E. Measurements were taken at depths of 107 to 640 m using the overcoring technique. Vertical stresses measured at some sites show close agreement with the calculated vertical stresses based on a 0.025 MPa/m depth gradient. Vertical stresses are almost identical to $P$, except at the shallower and deeper sites. At the 640-m-deep site at the West Elk Mine, $P$ was one and a half times the vertical stress, indicating a significant increase in the horizontal stress gradient at depth.

Stress measurements at the West Elk Mine provided a better understanding of ground behavior, and ultimately helped management in making ground support and mine design changes to reduce ground control problems. Adapted practices include increased primary bolt support density, routine use of standing secondary support in key gateroad entries, spot applications of roof carrier trusses in heavy ground, and allowances for reduced development rates in stress disturbed fault zones. Also, the potential for improving ground control with alternative longwall panel orientations was reviewed. Although no single-panel orientation was found to be optimal for all stages of mining, ranging from gateroad development through longwall retreat, the current N80°W orientation was determined to provide an acceptable balance of conditions.

In situ stress measurements using a deep down-hole overcoring method are being considered as part of the future drilling exploration program to guide and optimize future mine design.

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