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Mine Stability Mapping

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ABSTRACT

The high cost and limited flexibility of modern longwall systems has resulted in the need for mine engineers and geologists to predict possible adverse mining areas ahead of mining and to then design and implement suitable ground control solutions in a timely and cost effective manner. Therefore, over the last 30 years, geotechnical evaluations for coal mine planning and development have advanced from a minor afterthought to an important part of today's successful, high capacity, longwall mining operations. The latest iteration in this progression of improved analysis for predicting future mining conditions is a computer-based Stability Mapping System developed by West Virginia University. This system is designed to allow the mining engineer and geologist to effectively combine the mine geologic characteristics, stress influences, and structural features into an integrated stability map for use in mine planning and support design. This paper details the application of the stability mapping system to Bowie Resources, LLC, Bowie No. 3, multiple-seam longwall coal mine. At this mine, the prediction of adverse mining conditions using the stability mapping system allowed management to accurately adjust their support densities and operational procedures, and to successfully mine through difficult conditions safely and successfully.

INTRODUCTION

Historical Perspective of Longwall Mine Geotechnical Evaluations

Prior to the mid-1970s, most underground coal mine production was from room and pillar operations. The flexibility of room and pillar mining meant that the impacts of adverse geologic conditions could be fairly easily mitigated by simply changing the mine plan to avoid any bad areas. Beginning in the 1970s, coal mines began to adopt the mechanized longwall mining method. Initially, mines still remained relatively small. Throughout the 1970s and early 80s, a large coal mine would produced 2-3 million tons of coal per year. Since the late 1980s, the trend in the industry has been toward higher capacity longwall operations. With higher capacities, the capital costs of the longwall systems have increased dramatically for both the direct longwall mining equipment and the auxiliary support equipment. The typical cost for a new modern longwall mining system is about US $50 million for shields, face conveyor, shearer and related mining equipment. (Bowie is an averaged sized longwall operation, mining about 5 million tons per year.)

With the increased capital cost of modern longwall mining systems, the need for consistent, uninterrupted production is critical. Today, at the Bowie Mine, it is estimated that lost production on the longwall costs approximately $100,000 per day. Also, as longwall systems have become larger and more productive, the flexibility of the mine plan has greatly decreased. A modern longwall mine needs large blocks of continuous coal for economic development and production, and adverse geologic areas, in an otherwise suitable deposit, often need to be mined. The high cost and limited flexibility of modern longwall systems have resulted in the need for mine engineers and geologists to predict possible adverse mining areas and to then design and implement suitable ground control solutions in a timely and cost effective manner.

Therefore, over the last 30 years, geotechnical evaluations for coal mine planning and development have advanced from a minor afterthought to an important part of today's successful, high capacity, longwall mining operations. Initially, property evaluations simply focused on just coal quality and seam thickness. The mine management only needed to know: (1) that the coal quality was marketable and (2) that the reserve was large enough to justify the capital expense of acquiring mining equipment and undertaking mine development. Geotechnical evaluations were rarely performed, and geotechnical data were rarely collected. When collected, the geotechnical data generally consisted of basic lithologic descriptions of the roof and floor rocks along with field observations of the rock's response to coring.

These limited geotechnical data were all the mine planner had available with which to proceed. The types of data used in these early analyses often included: lithology, unit thickness, faults, linears, and fracture and jointing information. Occasionally, additional data were available including: RQD, insitu stresses, laboratory strength testing, clay mineralogy and notes on water encountered during drilling. Typically, these data were plotted on individual mylar sheets and contoured. These multiple mylar sheets were overlaid and the "dark areas", where multiple effects coalesced, were pinpointed as possible problem areas.

At this time, a very large amount of "engineering judgment" went into the decision to mine or not mine these areas. If the decision to mine was made, the orientation of the workings, the primary roof support and the supplemental secondary support became important parameters that the mine engineer had to design for the operations. The lack of comprehensive data and specific analytical tools made this process of geotechnical design very much an “art”.

The advent of the computer and the associated computer-aided drafting allowed the mine engineer and geologist to use individual drawing layers in much the same way that the original mylar sheets were used. At about the same time, increased collection of data from the initial exploration drilling program became more common. Additional data available to the mine engineer and geologist included: borehole logging for engineering rock material properties, more sample collection for laboratory testing and point load testing. This additional data and computer technology allowed engineers and geologists to improve upon the quality of their predictions and the accuracy of their support designs.

THE STABILITY MAPPING SYSTEM

The latest iteration in this progression of increased data collection and improved analysis for projecting future mining conditions is the development of a computer-based stability mapping system [1]. This new tool for mining engineers and geologists tightly integrates structural and geologic mapping with geo-mechanical stress analysis for use in mine layout planning and support design.

The stability of underground coal mine openings depends on three general factors: the immediate seam geology (the most critical), the stress conditions encountered in the mine, and the roof support used to provide additional support to the rock mass around the mine openings. The Stability Mapping System [1] is designed to integrate the geologic data available from surface and underground drilling programs, as well as from in-mine observations and measurements, with mine-level ground stress calculations. Prior to the application of the stability mapping system, these three factors had to be analyzed individually and combined via overlays or software layers in order to develop projections of the mine roof stability. With the assistance of the stability mapping system, many aspects of these three factors can now be readily analyzed and correlated in various combinations, resulting in a single, mine-wide stability map for use by mine operations personnel.

The stability mapping system was created as a run-time extension for the PC-based drafting program, AutoCAD®, because this software (coupled with SurvCADD®) is the preferred drafting and geologic modeling program for a vast majority of coal mines in the United States. Using the stability mapping system, the various mine-specific geological parameters are directly input into the system database. In conjunction with the geology, the stress conditions which impact the rock mass and mine workings are calculated separately using the boundary element program LAMODEL [2, 3]. This program determines the specific stress influences for the mine from the overburden, multiple-seams and subsidence. An overall stability map is generated by assimilating the geological parameters with the stress conditions. Each individual factor may be weighted separately as determined by the mining engineers and geologists to best represent the observed conditions in the mine.

The steps in a typical stability mapping analysis are [1]:

- Define, collect and input the critical geologic, structural and stress factors which have the most influence on the mine stability.
- Calculate a numerical grid for each critical factor.
- Determine an individual index from each critical factor.
- Weight the individual indices into an overall stability index.
- Plot and analyze the overall stability index on the mine map.
- Re-evaluate critical factors and weightings as necessary.

STABILITY MAPPING AT BOWIE

Bowie Resources, LLC, (BRL) operates the Bowie No. 2 and Bowie No. 3 Mines located east of Paonia, Colorado (Figure 1). The company has been extracting coal reserves from the Upper D and B Seams located in the Somerset Coal Field. The Somerset Coal Field is located on the southeastern margin of the Piceance Basin, which lies north of the Gunnison Uplift, west of the Elk Mountains, east of the Uncompahgre Uplift, and south of the White River Uplift. An estimated 1.5 billion tons of bituminous coal lay within the Somerset Coal Field of the Mesa Verde Formation. The regional structural dip of the Mesa Verde Formation is 3° to 5° to the north-northeast. The predominant jointing of sedimentary rocks is N 68° E to N 74° E in the basin, with secondary jointing at N 18° W to N 35° W.

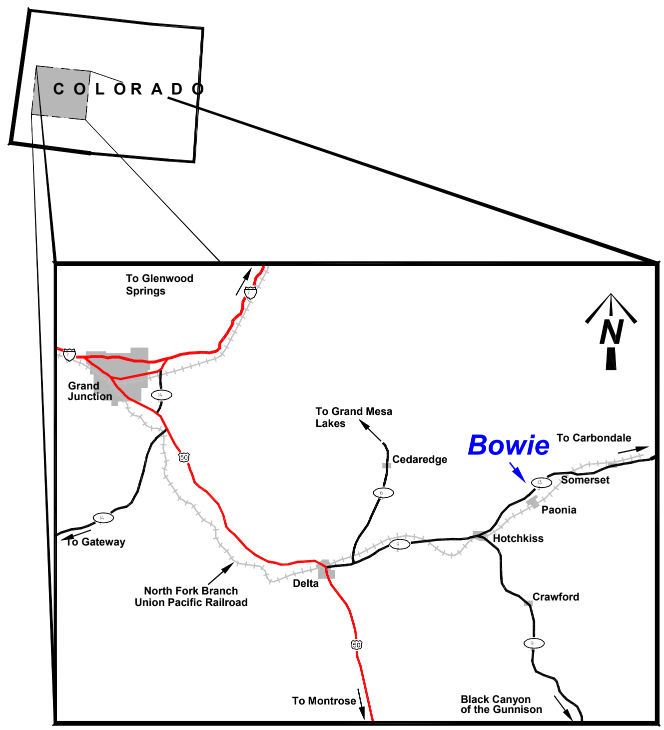

Figure 1. Mine site location map.

As Bowie Resources prepared to develop and mine the southwest mining district (see Figure 2) at the Bowie No. 3 mine, a stability map of the area was desired. Based on previous geotechnical evaluations and experience at the mine, eight critical geologic, structural and stress factors were determined for the stability mapping:

- Overburden Stress
- Multiple-Seam Stress
- Coal Mine Roof Rating
- Sandstone Channels
- Interburden Thickness to the Rider Seam
- Faults
- Slumps
- Warps

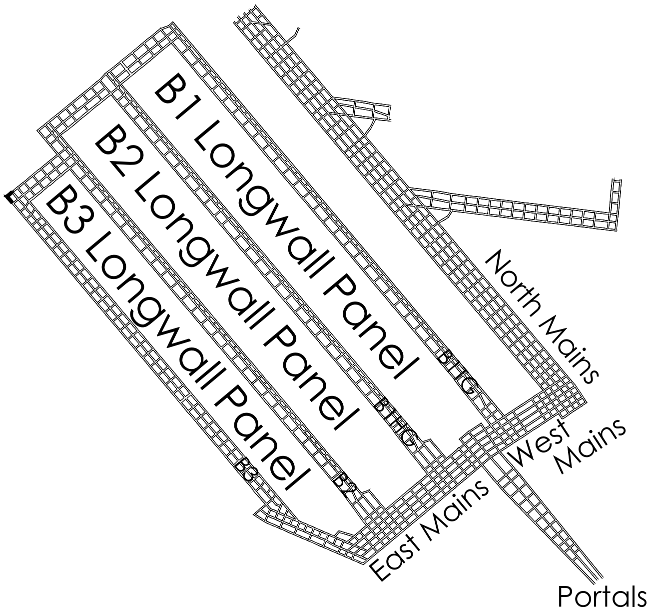

Figure 2. Southwest mining district longwall panel layout.

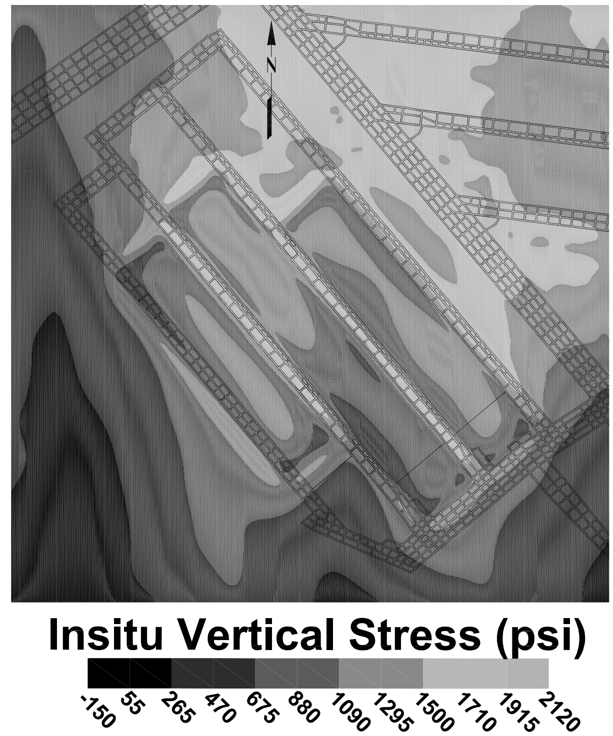

Figure 3. In situ stress in the southwest mining district.

Overburden and Multiple-Seam Stress

The LAMODEL program was used to generate the critical topographic and multiple-seam stress influences on the seam. First, the overlying topography was modeled with LAMODEL and a grid file of the topographic stress on the southwest district was created. In this southwest area of the coal reserve, the B-seam lies approximately 250 feet below mined out longwall panels in the D-seam of Bowie No. 2. These overlying extracted longwall panels create stress concentrations on the underlying B-Seam. To accurately incorporate these multiple-seam stresses into the stability mapping program, a LAMODEL analysis of the two mine plans was used to calculate a multiple-seam stress grid. A combination grid (insitu stress) of the topographic stress and the multiple-seam stress is shown in Figure 3.

Coal Mine Roof Rating

Generally, the most important geological factor in mine stability is roof strength. Prior to adopting the stability mapping system, roof strength at Bowie was primarily analyzed using the NIOSH Coal Mine Roof Rating (CMRR) system [4, 5]. The CMRR integrates the rock strength within the bolted interval to create a numerical rating from 0-100, with 100 being the strongest, most stable roof. For the stability mapping process, the strength of the roof rock in the southwest mining district was analyzed using drill core in conjunction with a point load tester at various points. From these point CMRR values and knowledge of the specific depositional features in the area, a contour map of the CMRR was created. For creating the CMRR contour map, depositional informational was critical. The CMRR trended with relation to the sandstone channels and the interburden thickness to the rider seam (see later sections). By manually interpolating these depositional trends into the contours, a much more accurate CMRR map was produced than if the computer had been used to simply interpolate the limited point values. The final CMRR contours were then used to create an index grid and this grid was weighted as a major geological factor within the stability mapping system

Sandstone Channels

In the northwest corner of the Southwest mining district, a couple of sandstone channels exist in the roof above the B seam (see Figure 4). These channels have a lenticular cross section with the maximum thickness along the main axis and thinning out towards the edges over a distance of several hundred feet. In some areas, the sandstone is directly on top of the coal, but generally, the sandstone channel is up in the immediate roof layers. With the sandstone channels, the roof is most competent in the middle thick section. Towards the edges of the channels, the thin sandstone and differential compaction causes poor roof conditions. Contours of the roof stability due to the sandstone channels were manually created based on the known channel axes and channel widths. These contours were then used to create an index grid and included in the stability mapping.

Interburden Thickness

On the eastern side of the Southwest mining district, there is a rider coal seam above the main bench of the B seam. This rider is far from the main bench in the eastern corner, but gradually gets closer until it merges with the main bench of the B seam as shown by the interburden thickness contours in Figure 4. When the interburden is less than two feet thick, it typically falls out when the underlying coal is initially mined and it is not much of a problem. When the interburden is between two and six feet thick, it gets bolted on initial mining, but frequently falls as mining progresses and causes considerable support problems. When the interburden to the rider seam is greater than six feet thick, the roof generally remains stable. For the stability mapping, the interburden thickness contours were used to create a grid where the roof areas with an interburden between two and six feet were considered unstable.

Faults, Slumps and Warps

As shown in Figure 5, the southwest mining district of Bowie No. 3 Mine is bracketed by the major Mains Fault in the northeast and the B3 Fault in the southwest. Also, throughout the district,

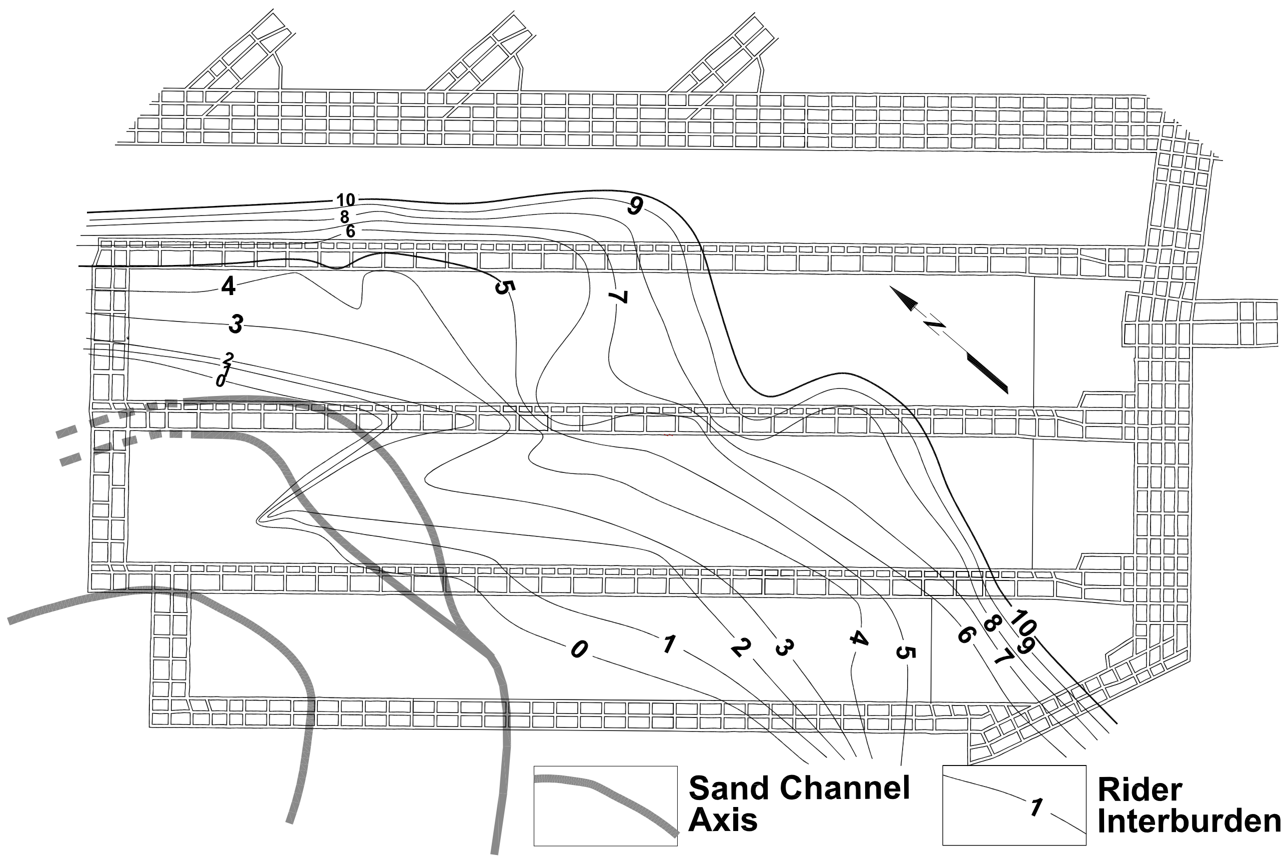

Figure 4. Sandstone channels and rider interburden thickness.

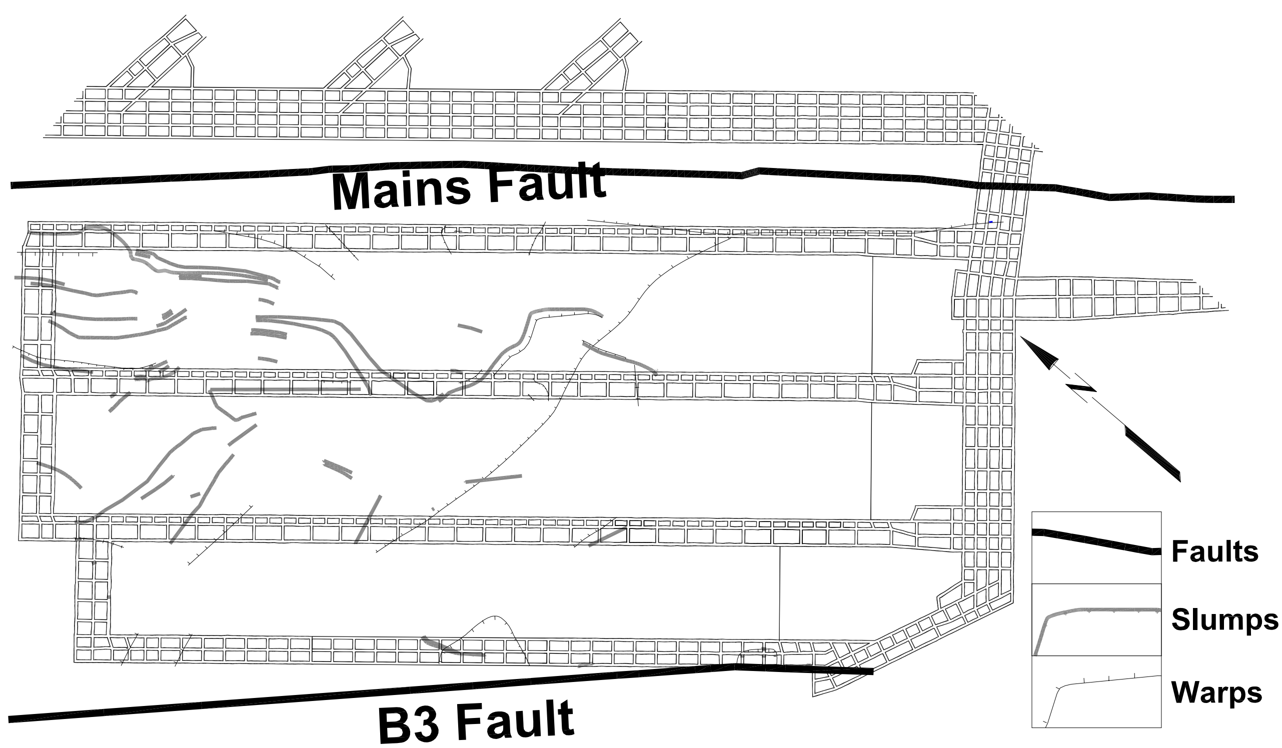

Figure 5. Faults, slumps and warps in the southwest mining district.

there are "slumps", minor faulting where roof rock is pushed down into the seam, and "warps" where the coal seam changes elevation abruptly. In relation to stability conditions, these types of linear structural features have a zone of influence on either side proportional to the seam disturbance. At Bowie, a zone of influence of 300 ft on either side of the major faults and 10 feet on either side of the slumps and warps was determined to be appropriate. Within this zone of influence, the adverse conditions are greatest at the center and linearly decrease to zero at the edge of the influence. The stability mapping system has a function that allows the user to easily generate these influence zones and associated grids from the AutoCAD trace of the linear feature.

Final Stability Map

Once grids were created for each of the critical geologic, structural or stress factors, they were individually weighted and combined into a stability map. In the southwest mining district, several different stability maps were produced with different sets of weighting. The final weightings (see Table 1) and the associated final stability map (see Figure 6) was the one which most accurately represented the observed conditions in the mined out portions of the district.

Table 1. Critical Factor Weighting

Critical Factor	Final Weighting
Overburden Stress	20
Multiple-Seam Stress	15
CMRR	20
Sandstone Channels	10
Interburden Thickness	20
Faults	20
Slumps	10
Warps	5

GEOTECHNICAL ANALYSES AND OBSERVED MINING CONDITIONS

Before mining commenced in the Southwest District of Bowie No. 3 Mine, geologic data was developed from surface-based exploration drill holes. Also, a follow-up drilling program of 12 holes was conducted from underground in the longwall gateroad entries in the overlying D-seam. (A detailed description of the geologic data management system used at Bowie Mine is given in [4]). The drilling based geologic data indicated:

- No adverse geology in the B1 and B2 panels.
- No unusual levels of methane in any of the panels.
- A local zone of squeezing holes and soft coal was encountered along part of the proposed B3 gateroad.
- Core testing and point load testing indicated that coal strengths were significantly reduced compared to normal B-seam coal strengths in the North Fork valley.

Development mining proceeded without incident in the East and West Mains and the first half of the B1TG and B1HG gateroads. However, approximately halfway into each gateroad, mining encountered small faulting in the seams as well as localized zones of low-angle shears in the coal. These seam disturbances significantly impacted mining productivity. Development rates slowed with reduced cut lengths and increased bolt installation time due to reduced bolt spacing. Roof bolt standards were changed from 6-ft fully-grouted, headed rebar to a minimum of a 7-ft torque-tension bolt. Rib rashing was also more pronounced in these disturbed zones. Similar conditions were also encountered in the B1 longwall set-up room.

Based on the conditions encountered during development, the available observational and lithographic data were reanalyzed. The initial CMRR analysis indicated very low CMRR values (about 35-40) in the back half of the B1 longwall panel. Observational condition mapping in the gateroads also indicated these disturbed areas in the headgate and tailgate would be problematic during longwall retreat. Enhanced support was designed for the B1 tailgate area and the future tailgate area of the B2 longwall panel (B1HG #1 entry). This enhanced support consisted of:

- 12-ft cable bolts, 4 per row, with heavy duty roof mats, 5-ft maximum row spacing.
- 24-in Burrell™ cans, 2 cans per rows, maximum 8-ft skin-to-skin spacing.

As longwall mining progressed, procedures for dealing with the slumps on the face were developed. Initially, the practice was to mine underneath rock partings and faults in the face. Several minor roof falls and one major roof fall on the face indicated that the proper procedure was to maintain the cutting horizon by mining through the slumps, rather than cutting below the rock slumped into the face.

Primary torque-tension bolts and secondary support from the 12-ft cable bolts and 24-in cans adequately controlled the roof in the B1 tailgate. However, there was significant floor heave in the B1 tailgate. This floor heave was attributed to a slump which ran parallel with the B1 tailgate pillar and weakened the surrounding coal. The cans generally provided adequate control for the floor heave. Overall, tailgate conditions did not adversely impact longwall productivity.

Problems did develop in the B1 headgate belt entry from a combination of roof sag and floor heave creating squeezing conditions just outby the longwall face. Longwall operations were interrupted while the belt line was partially removed for 500 ft and the floor was re-graded to remove the heaved coal. Three to four feet of floor heave also occurred along the future tailgate for the B2 longwall. In this zone, additional standing support was installed consisting of 100-ton props and roof channel on 6-ft centers.

About half way through mining of the B1 longwall panel, Bowie obtained and implemented the stability mapping software and procedures. Using existing data, a stability map for the Southwest District was generated as shown in Figure 6. Having mined the first half of the B1 panel allowed us to compare predictions of mining conditions in the stability map with actual mining experience. This comparison enabled validation of the assumptions and optimization of the weightings used in creating the stability map. Correlations between predicted and actual problem zones were very high. As seen in Figure 6, the first half of the B1 panel was projected to have adverse mining conditions, and this was indeed the case.

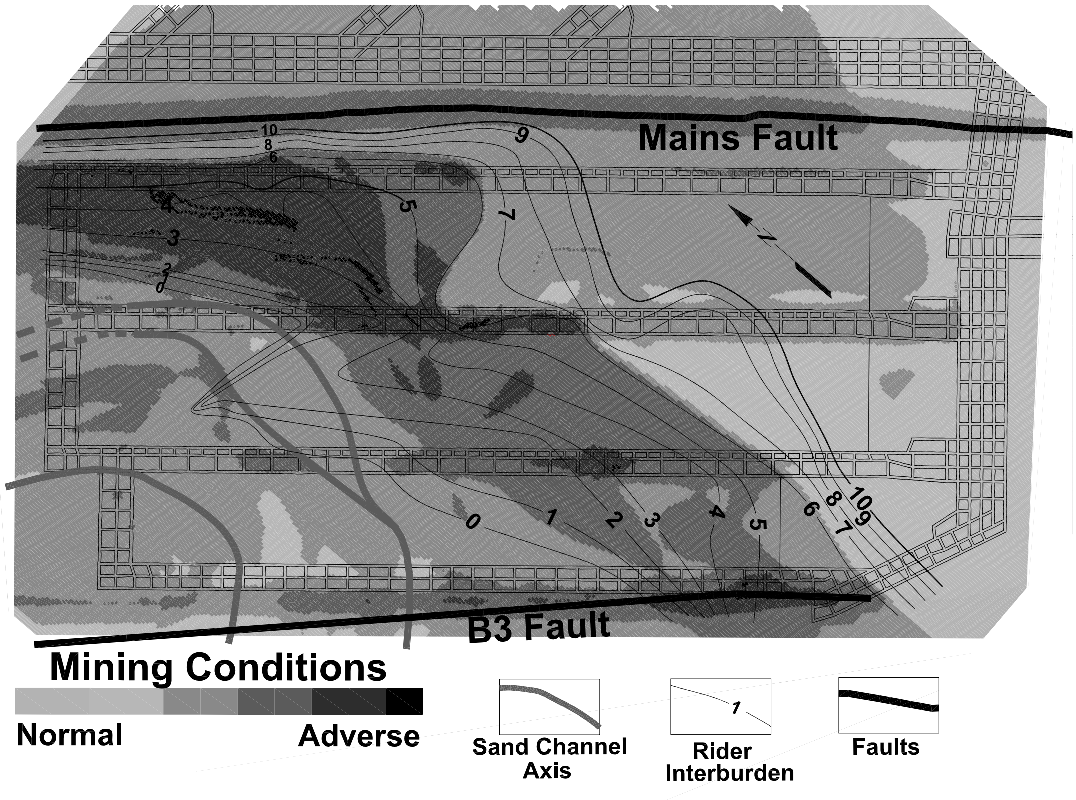

Figure 6. Southwest mining district, Final Stability Map.

CHANGES

The stability mapping indicated that the middle third of the B2 longwall panel would most likely experience difficult mining conditions. Based on experiences with the poor mining zone in the B1 longwall panel, the following operational and ground control changes were implemented for the B2 longwall panel:

- Cross-panel radar imaging [6] was performed to better define possible problems areas within the longwall panel.
- Pumpable cribs were installed in between existing supports in the tailgate.
- The geological model and CMRR projections were continuously updated and incorporated into the projected stability map.
- Approximately 2,500 feet of panel belt line was removed and the roof rebolted with 18-ft post tensioned cable bolts and heavy duty roof mats on 4-ft centers.
- Transfer lines for polyurethane grout were permanently installed in the Brettby, and a pair of transfer tanks was fabricated as part of the tailgate drive assembly.
- The future tailgate for the B3 panel was divided into stability zones, and the type and density of supplemental support were tailored to the expected conditions.
- Two additional surface-based gob vent boreholes were drilled in the problem zone to provide for additional ventilation of methane out of the gob.
- Budget projections for production through the B2 poor mining zone were reduced.
- Weekly quality meetings focused on reviewing past mining experiences and predicting future ground response to longwall mining. Lessons learned were incorporated into future longwall operations and support plans.

RESULTS

Mining operations to date on the B2 longwall panel have shown that the stability mapping system successfully indicated potential problem roof zones on the longwall face. Stability mapping successfully predicted problematic headgate and tailgate zones. Additional cable bolting in the headgate resulted in good headgate mining conditions. It was learned that tailgate floor heave was principally driven by the slumps. Based on B2 tailgate conditions, 12-ft, un-tensioned cable bolts only marginally control the roof. Standing support consisting of a single row of cans was inadequate to control floor heave. A double row of cans was more successful in controlling floor heave, which primarily impacted longwall mining operations through restricted air flow volumes. However, the efforts and operational plans developed from projecting problems zones through the stability mapping system allowed Bowie Resources to successfully mine through these difficult conditions safely and successfully. This foreknowledge of mining conditions allowed BRL to avoid the alternative of cutting the B2 and B3 longwall panels about in half and losing over 2 million tons of developed reserves.

ACKNOWLEDGEMENTS

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