SME Annual Meeting
March 1-3, 1999, Denver, Colorado

Preprint 99-8

Long-Term Stability for Two-Seam Mining at OCI's Big Island Mine

J. F. T. Agapito
R. R. Goodrich
Agapito Assoc. Inc.
Grand Junction, CO

M. L. Andrews
OCI Wyoming, L.P.
Green River, WY

ABSTRACT

Two flat-lying trona seams 3- to 3.5-m thick, approximately 10 m apart, and at depths of 250 m are mined by room-and-pillar at OCI's Big Island Mine in Wyoming. Continuous miners and a yielding pillar system have contributed to improvements in resource recovery and productivity.

Long-term stability with minimal subsidence is needed for a large portion of the mine beneath the Green River channel. This was investigated by computer modeling in 1990. Although results of the study indicated good long-term stability, recommendations were made for stress determinations to verify the model. Stress determinations made in 1997 showed pillar stresses 10% to 20% higher than the model stresses, and barrier pillar stresses 10% to 15% lower. This implies that higher panel stresses will be transmitted from the upper to the lower seam. A stability evaluation of the lower seam is planned before two-seam mining to assess entry widths and support requirements.

INTRODUCTION

OCI's Big Island Mine and Refinery are located 40 km northwest of Green River, Wyoming. Mining operations supply trona, a sodium mineral, to the refinery for the production of soda ash. Continuous mining machines are used to extract the trona from two 3- to 3.5-m-thick, flay-laying seams at depths of 250 and 260 m, respectively. Mine production in 1997 was 2.85Mt.

The trona deposits in southwest Wyoming occur in the Wilkins Peak Member of the Green River Formation. In addition to trona, the strata in this member consists of shales interbedded with oil shales, marlstones, limestones, mudstones, and tuffs. The overburden consists mostly of a series of thick siltstone, sandstone, and marlstone strata.

Room-and-pillar design has evolved through the years from drilled and blasted square or nearly square, full-overburden support pillars to continuous machine-mined, thin, rectangular (yield) pillars. Improvements in resource recovery on the order of 8% was achieved by reducing pillar areas by 42% and increasing entry widths by 32% (Agapito and Hunter 1989). The wider rooms and narrower pillars allowed significant improvements in productivity due to shorter and fewer equipment moves and increased tonnage at the face.

Two-seam test mining in 1977 using 11-m by 12-m pillars and 6.7-m-wide entries indicated good stability with little stress interaction between the seams (Agapito et al. 1978 and Kneisley 1982). Two additional two-seam panels were mined in the 1980s immediately to the south of the test panel without major ground control problems. All the two-seam mining was accomplished using drilling and blasting, with the upper bed being mined after the lower bed. Two-seam mining has not been accomplished yet using continuous miners and yield pillars.

This paper presents an evaluation of long-term stability for two-seam mining with continuous miners and yield pillars. It is based on available single-seam experience, stress determinations, and modeling to predict time-dependent stress changes.

GEOTECHNICAL BACKGROUND

Strata in the vicinity of the two trona seams is formed by beds of marlstones and shales containing thin oil shale beds (Figure 1). Weak shale/mudstones with irregularly dispersed trona forms the immediate roof of both seams. Top trona has been left, mostly when using drilling and blasting techniques, to reinforce the roof. Irregularly spaced, steeply inclined, natron-filled joints occur in the roof shales, which sometimes can cause stability problems. Natron is a hydrated sodium carbonate which loses its strength when exposed to the air. During mining, particular attention is paid to the formation of wedges and blocks by these joints that may require support reinforcement.

Except for the marlstones, the trona is stronger and stiffer than the strata in the vicinity of the openings (Table I). Previous rock mechanics programs indicated that pillar yielding occurs when the pillar sizes are reduced to certain dimensions. This was established by overcore measurements made at various times after mining to the center of the pillars (Agapito and Hunter 1989). Yielding was defined as the average vertical stresses decreased in

Table I. Summary of Mechanical Properties (Kneisley 1982)

	Laboratory tests					*In situ* tests		
Rock type	Uniaxial compression strength (MPa)	Elastic modulus (GPa)	Poisson's ratio	Angle of internal friction (degrees)	Cohesion (MPa)	Modulus of rigidity[a] (GPa)	Angle of internal friction[b] (degrees)	Cohesion[b] (MPa)
Trona	44.1	18.10	0.20	43	9.9	7.58	30	3.2
Shale/mudstone	25.9	2.95	0.20	33	4.2	4.34	32	2.0
Oil shale	29.7	2.83	0.16	25	10.7			
Shale	31.1	3.02	0.22			3.79	30	1.1
Marlstone[c]	44.7	8.41	0.21	43	15.7			
Marlstone[d]	90.6	19.24	0.16	57	12.6	7.21	24	3.9

[a] Borehole cylindrical pressure cell test
[b] Borehole shear strength test
[c] Near floor of upper bed
[d] Floor of lower bed

time. Comparisons were made to tributary area stresses and to previous measurements. For drilled and blasted square pillars, this occurred at stress levels of 20 to 25 MPa when the pillars were 9- to 10-m square and the panel width was 100 m. For continuous mining, yielding occurred at lower stress levels with 6-m-wide by 29-m-long pillars, at about 17 to 20 MPa in 135-m-wide panels.

The introduction of continuous miners and yield pillars has been very successful for both resource recovery and productivity. Figure 2 shows a Joy 12 HM10 continuous miner in a 9-m-wide entry. Improvements in resource recovery of 8% were made, equivalent to about 142 t/m of panel advance. Entry widths were increased from 6.7 to 9 m. This increase, and the narrower pillars, allowed improvements in productivity due to shorter and fewer equipment moves, and increased tonnage at the face. Panels are on the average 240-m wide and 800- to 1600-m long, separated by 20-m barrier pillars. Yield pillars are mined in a chevron pattern, 6.5- to 8-m wide, separated by 9-m-wide rooms and 4.5-m-wide crosscuts (Figure 3).

TIME-DEPENDENT STRESSES

In order to evaluate long-term stability, time-dependent stresses were calculated through computer modeling. Instrumentation and observations indicated that pillar yielding within the panels causes the overburden loading to be transferred to barrier pillars. Good long-term stability is needed to minimize subsidence over a large portion of the mine which lies under the Green River. Thus, "pressure arching" must remain stable over the panels.

Computer modeling was performed using the codes EXPAREA and MINAP to calculate stresses. EXPAREA is a quasi three-dimensional code that uses the displacement-discontinuity technique to calculate vertical stresses and deformations in large, tabular, seam-type deposits. It incorporates linear elastic, elastic-plastic, elastic-strain softening (yield), and bilinear-backfill constitutive models for modeling pillar yield and caving. This code has been used for about 20 years at Agapito Associates, Inc. (AAI) in many mines and, whenever possible, models have been verified through experience and *in situ* measurements.

MINAP is a two-dimensional, displacement-discontinuity code that can be used to calculate vertical and horizontal stresses and generate safety factor contours. The safety factors are calculated according to specified strength criteria, and are particularly useful in evaluating potential areas of instability.

The methodology used in the study was to calculate time-dependent stresses in the upper seam (after mining) and in the lower seam (before mining) using EXPAREA. MINAP used the EXPAREA output at specified times to evaluate the interburden safety factors after mining the lower seam. In addition to overburden loading, the lower seam stresses are caused by pillar stresses in the upper seam. A series of time-dependent stresses were calculated from immediately after mining to 20 years after mining. Little continuous machine mining had been done at the time. Safety factors were calculated according to Mohr-Coulomb criteria developed from *in situ* testing performed by the U.S. Bureau of Mines (USBM) on the two-seam test panel (Kneisley 1982).

Time-dependent strains and stresses are related by the following equation in the EXPAREA code:

$$\epsilon = A\, t^{a}\, \sigma^{b}\, T^{c} \tag{1}$$

where
ϵ = strain
t = time
σ = stress
T = temperature
$A,\ ^{a,\,b,\,c}$ = constants

There were three important judgements made reflecting uncertainties in rock mass properties and in-ground behavior. These judgements were made on the conservative side. The first was with regard to the constants *b* and *c* in equation 1. Since there was no test data from trona to develop these constants, data from tests on salt were used. This would result in higher yielding and stress transfers because of softer salt properties. The result was that the steady state of little or no yielding would take longer to be reached in the model than in real life. At the same time, upper bed pillar stresses would be lower than in reality, resulting in lower stress transmission to the lower bed. To overcome this, the second and third judgements were made. These consisted of assuming the interburden (lower bed roof) material properties in the MINAP analyses were equivalent to that of shale (the weakest strata), and in decreasing the interburden thickness by 2 m.

Pertinent input material properties and model dimensions are summarized in Table II. Figure 4 shows the panel layout and area evaluated in the analyses.

RESULTS OF THE ANALYSES

Analyses results are shown as plan view stress maps in Figures 5 and 6. Note that the area modeled is larger than shown in these figures because of lines of symmetry in the north, east, and south edges of the stress printouts. Stresses are represented in color patterns at various levels from 0 to 40 MPa. The blue represents the overburden pre-mining stress level. Figure 5 shows the upper seam stresses at four time periods—immediately after mining and 5, 10, and 20 years after mining. The location of stress changes can be seen clearly as color changes. Pillar yielding causes a shift of overburden loading onto barriers. Immediately after mining the stresses are highest (30 MPa) at the end of the narrow panel pillars. This is corroborated by fracturing and some spalling observed at these locations. The core of the larger rigid pillars are at overburden stress levels of 6 MPa. The high stresses have faded out from the ends of the panel pillars as stresses are being shifted onto the barriers. High skin stresses have begun to be transferred to the cores of rigid pillars, and barrier pillar loading has become quite evident. These stress transfer trends continue with time as shown at 5, 10, and 20 years after mining; however, the rate of stress transfer decreases with time. At 20 years, the abutments are almost fully loaded with stress levels of 20 to 28 MPa. The panel pillars are now slightly below pre-mining stress levels of about 6 to 7 MPa. From Figure 5, a "pressure arch" can be visualized over the panel with abutments on the barriers.

Figure 6 shows the vertical stresses induced in the lower seam by upper seam mining for three time periods—immediately after, 5 years after, and 20 years after mining. The lower seam is unmined for all time periods. The stress footprints of the upper seam pillars are clearly seen. The stress transfer with time indicates that at 20 years the panel area stresses become lower than the overburden stresses, but some areas under the barriers are at 15 to 20 MPa. Columnization of barriers is important to avoid mining in the lower seam at these stress levels, otherwise support reinforcement and narrower entries will be needed.

Table II. Material Properties and Model Dimensions

Material Properties		
Description	**Symbol**	**Nominal Value**
Young's modulus of rock mass	E_m	20.7 GPa
Poisson's ratio of rock mass	ν_m	0.2
Unit weight of overburden rock	γ	2.8 t/m^3
Young's modulus of trona seam	E_s	27.5 GPa
Creep constant	A	138×10^{-46} MPa
Time exponent	a	0.8
Stress exponent	b	3.0
Temperature exponent	c	9.5
Model Dimensions		
Upper seam depth	250 m	
Seam interburden	8 m	
Seam thickness	3 m	
Panel width	240 m	
Panel pillars	6.5-m wide × 25- to 30-m long	
Room widths	4.5 m	
Crosscut spans	18 m	
Barrier pillar widths	9 m	
Mains pillars	12-m wide × 24-m long	
Mains entry widths	7.5 m	

Figure 7 shows the interburden safety factors from the MINAP analyses for periods immediately after and 5 years after mining. Columnization of pillars was assumed between the beds. A relatively large area with a safety factor of 1 or less occurs in the interburden immediately after mining. It should be noted that a safety factor of 1 shows a 50% chance of rock mass fracturing but does not imply collapse. Thus, the safety factor contours should be interpreted only as areas of potential fracturing and bed separation, and not as potential collapse areas. At 5 years, the safety factor areas of 1 or less have decreased to two small areas at the corners of the entries. Fracturing in these areas would probably be easily controlled with roof bolting. The MINAP analyses indicate that there should be a period of time before mining the lower seam (in this case 5 years) to allow stresses in the upper bed pillars to decrease.

The major conclusion of the 1990 study was a prognosis of good long-term stability. Since then approximately 20 panels have been mined—12 in the upper seam and 8 in the lower seam. However, two-seam mining with continuous miners has not been performed. Figure 8 shows a typical intersection in a belt entry at the center of a panel where diagonal spans reach 15 m. Stability has been excellent.

MODEL VERIFICATION

A recommendation for periodic stress determinations was made upon completion of the analyses to compare the model and *in situ* stresses. This was done in 1997, 7 years after mining the panel addressed in the study, the UB N4E Panel in the upper seam. Stress determinations were made using the overcoring technique in two panel pillars and in the side barrier pillar as shown in Figure 4. Figure 9 compares the modeling and measurement results. While the measured pillar stresses are about 10% to 20% higher than the modeled stresses, the barrier pillar stresses are almost 10% to 15% lower. Thus, pillar yielding is lower than originally projected, in part due to the salt constants used in the time-dependent analyses. This results both in lower long-term overburden deformations and in higher stress transmissions to lower seam panels.

FUTURE WORK

The stress determinations provided one point of verification for the stress/yielding time curve. In about 5 years, stress determinations should be made at the same locations to verify stress trends and determine whether or not the curve has flattened out. It is likely that yielding will stop well ahead of the model predictions.

A more detailed lower bed stability evaluation should also be made based on measured stress levels, recent interbed geologic and material property data, and more sophisticated analyses. As compared to the two-seam mining performed 20 years ago, the present continuous miner practice leaves little or no trona in the immediate roof beneficial to stability. In addition, the present entries are 32% wider and measured pillar stresses 82% higher.

CONCLUSIONS

The application of practical rock mechanics at OCI's Big Island Mine has helped to modify and improve the mine design. Higher resource recovery and productivity have been achieved by introducing continuous miners and a yielding pillar system with wider rooms and narrower pillars rather than the drilling and blasting system.

Subsidence needs to be minimized or avoided in a large portion of the mine below the Green River. Two-seam mining should be accomplished within this constraint, while maintaining the current design, equipment, and mining practices required for good cost control.

The long-term stability study in 1990 predicted good stability and helped management to decide to adopt the current design. About 20 single-seam panels have been mined with good stability results.

Stresses predicted by modeling were checked in 1997 by using overcoring measurements. Results indicated that pillar stresses were 10% to 20% higher and barrier pillar stresses 10% to 15% lower than predicted. Although this results in lower long-term deformations, higher stresses will be transmitted to lower seam panels. An evaluation of the lower bed mining is needed to assess entry spans and ground support requirements for maintaining good short- and long-term stability.

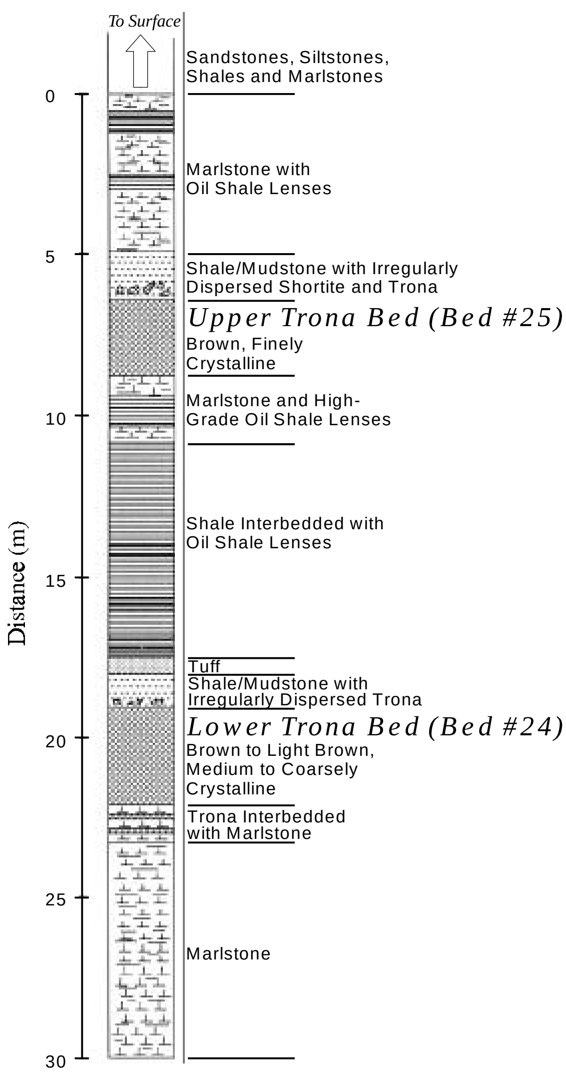

Figure 1. Geologic Column in the Vicinity of the Trona Seams

ACKNOWLEDGMENTS

The authors are indebted to OCI Wyoming, LP, who commissioned and allowed publication of this paper, and especially to Mr. Ray Richardson, Mine Manager, for comments and review.

REFERENCES

Agapito, J.F.T. and R.V. Hunter (1989), "Rock Mechanics Program Helps Improve Trona Recovery at Stauffer's Big Island Mine in Wyoming," Mining Engineering, January, pp. 24–28.

Agapito, J.F.T., J.W. Bennett, and J.P. Hunter (1978), "Rock Mechanics for Two Seam Mining at the Big Island Trona Mine, Stauffer Chemical Company of Wyoming," Proceedings, 19th U.S. Rock Mechanics Symposium, Stateline, NV, May 1–3, pp. 57–64.

Kneisley, R.O. (1982), "Rock Mechanics Investigation on Two-Bed Trona Mining, Green River, Wyoming," U.S. Bureau of Mines RI 8598.

Figure 2. Continuous Miner in a 9-m-wide Entry

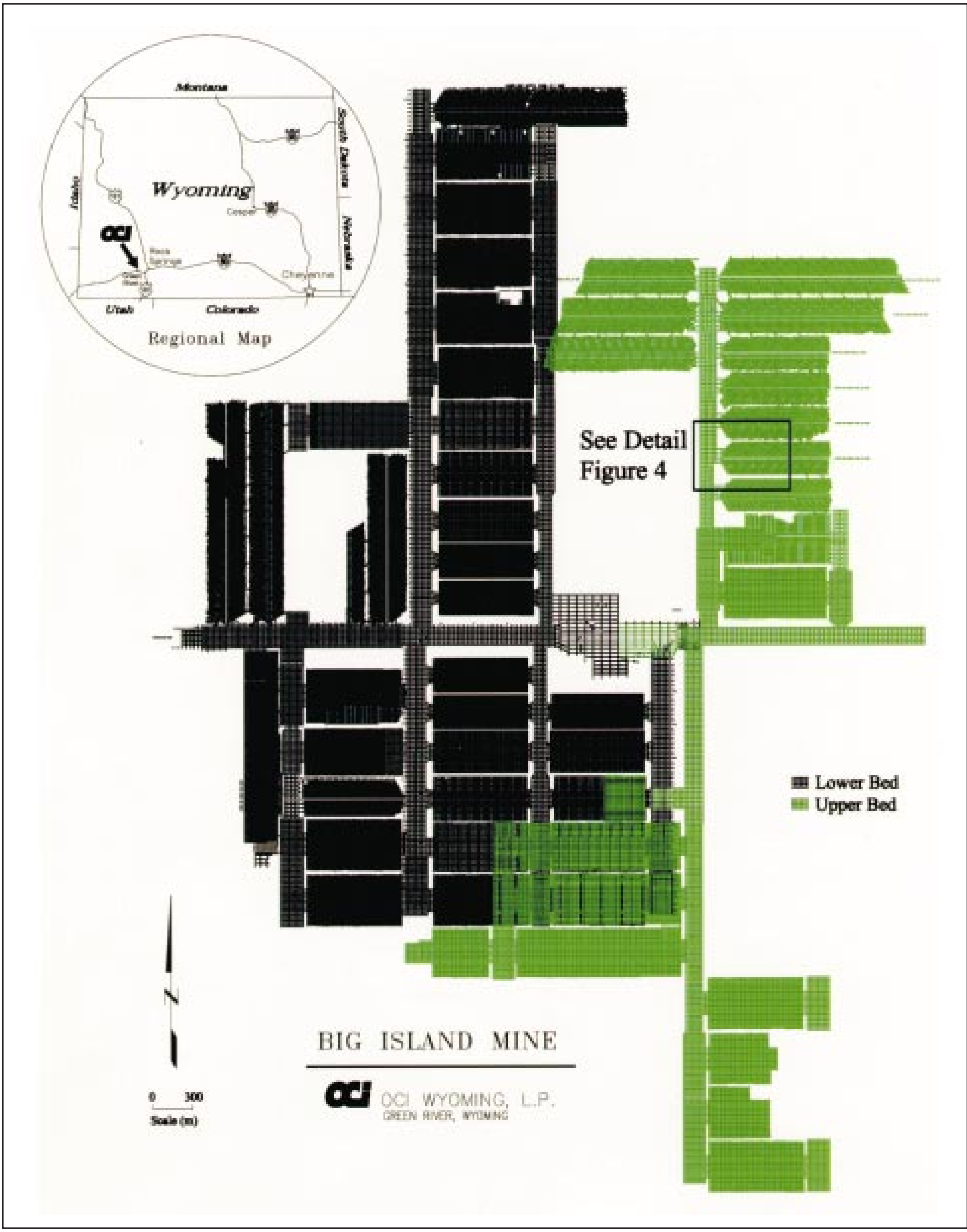

Figure 3. Location and Map of Big Island Mine

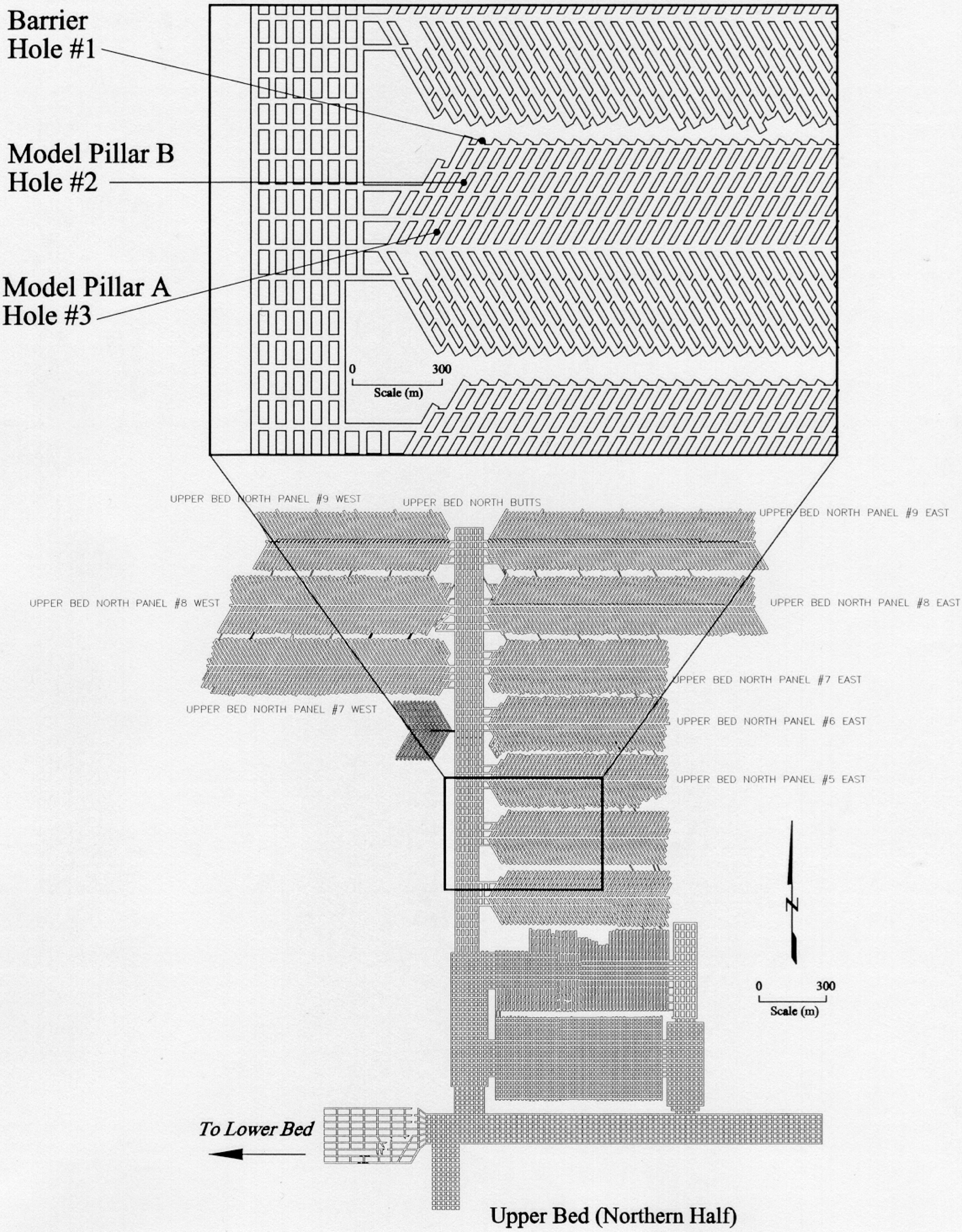

Figure 4. Panel Layout Evaluated in Analyses and Overcore Locations

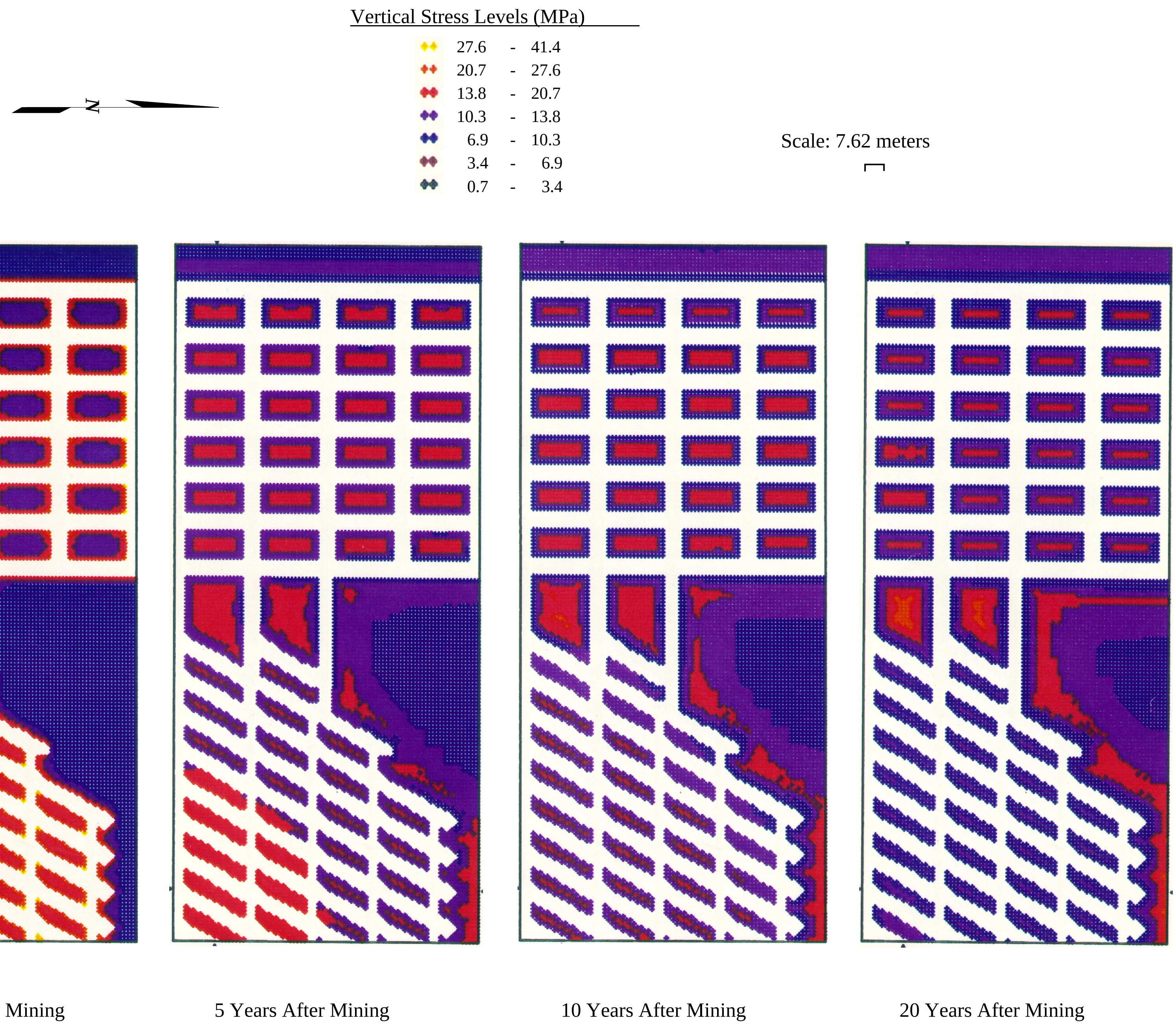

Figure 5. Changes in Upper Seam Stresses with Time

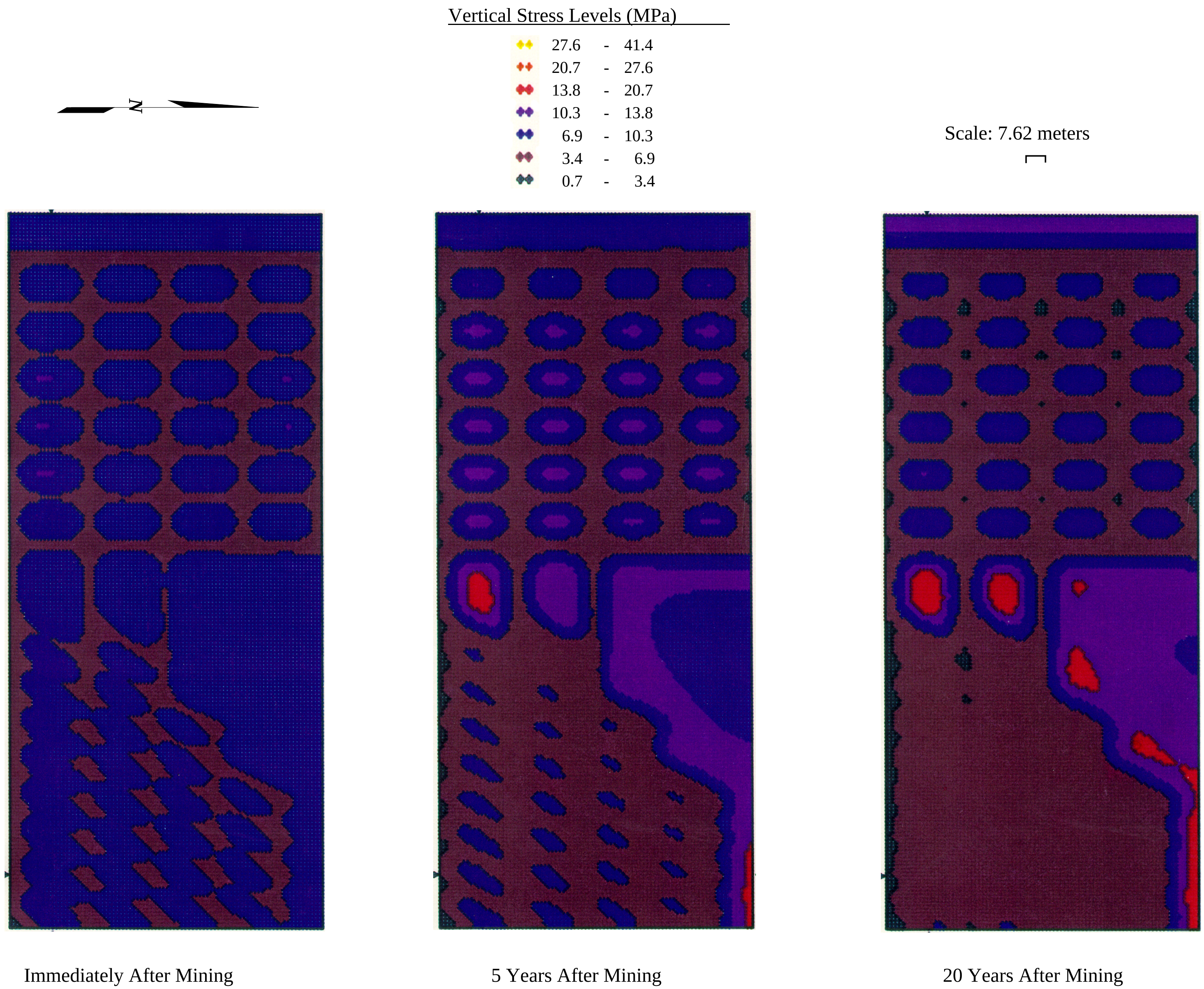

Figure 6. Lower Seam Stresses Immediately After Mining, 5 and 20 Years Later (Lower Seam Unmined)

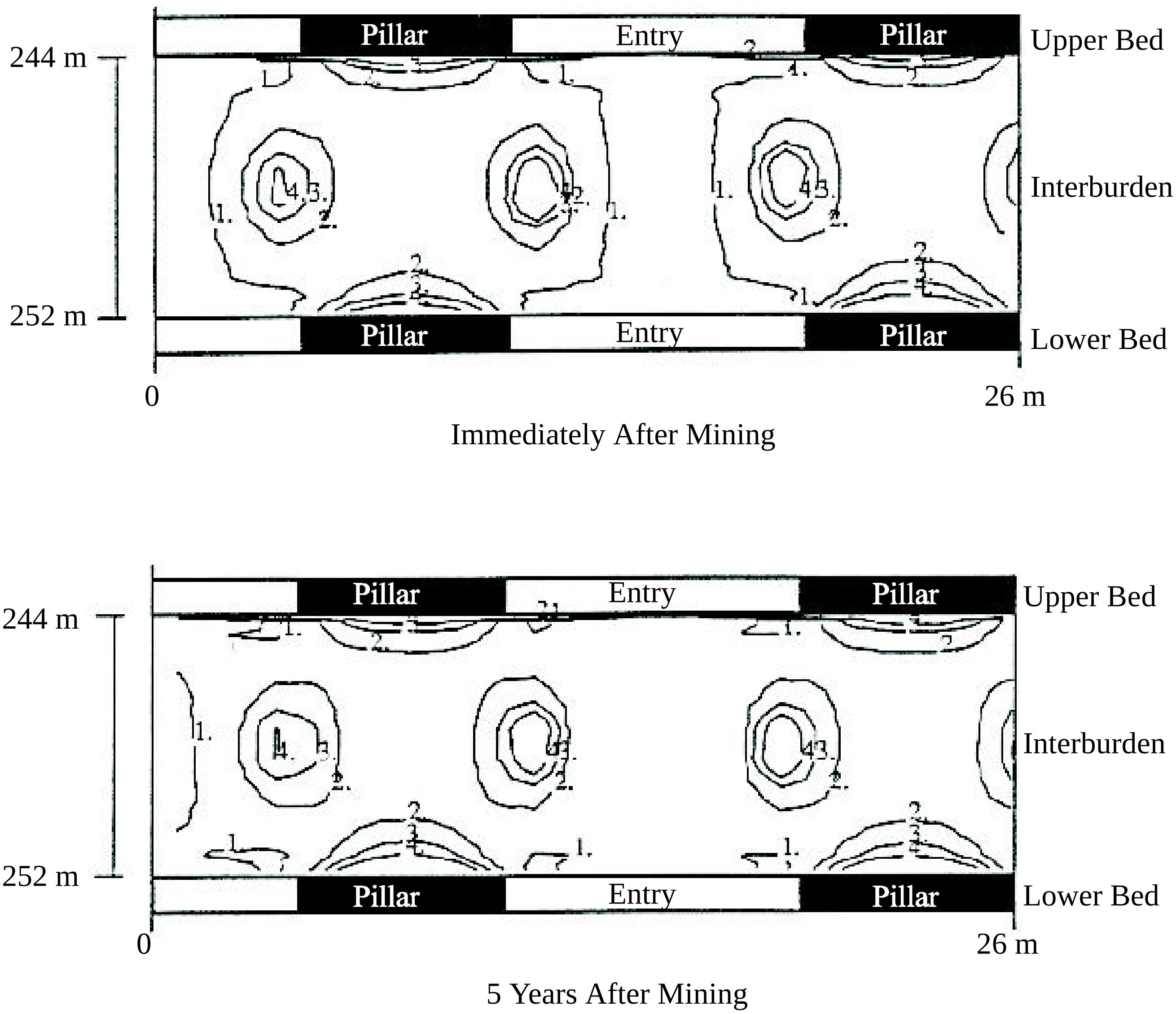

Figure 7. Interburden Safety Factors Immediately After Mining and 5 Years Later

Figure 8. Typical Intersection in a Belt Entry

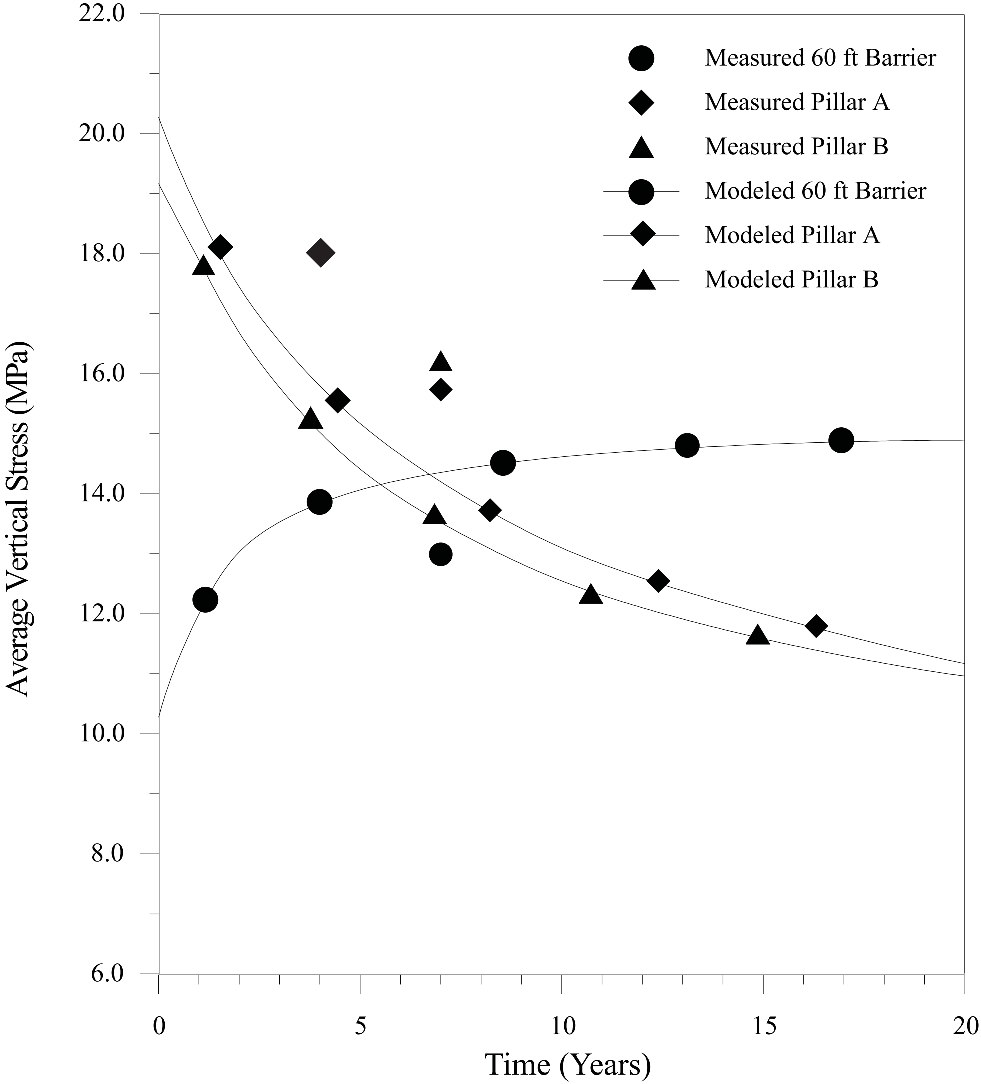

Figure 9. Comparison of Modeled and Measured Stresses