SME Annual Meeting
Feb. 23-25, Denver, Colorado

Preprint 04-131

STRESS ISSUES IMPACTING DESIGN AND STABILITY AT OCI WYOMING'S BIG ISLAND TRONA MINE

J.F.T. Agapito
L. J. Gilbride
Agapito Assocs., Inc.
Grand Junction, CO

K. Hollberg
OCI Wyoming, LP
Green River, WY

ABSTRACT

Room-and-pillar mining at the Big Island Mine uses narrow, yield (i.e., load transferring) pillars to achieve high resource recovery and productivity. Two flat-lying 3- to 3.5-meter (10- to 11.5-ft) seams are mined. The interburden between the seams is about 10 meters (33 ft) and the cover depth is 250 to 330 meters (820 to 1,080 ft). Most of the mining has been single-seam, but two-seam mining will begin in the near future. Yield pillars minimize stress transfer between the seams. However, it is important that good long-term stability be maintained to prevent subsidence over a large portion of the mine beneath the Green River channel.

Three stress issues impacting stability are discussed in this paper: (1) higher-than-gravity vertical pre-mining stresses, (2) time-dependent stress transfer or arching, and (3) stresses induced by strata gas. Although the stress environment and behavior is not fully understood, steps have been taken in mine design and operations to minimize impacts to stability. Stress determinations have been very important to verify analytical predictions used in mine design and in long-term stability assessment.

INTRODUCTION

Three stress issues at OCI's Big Island Mine present challenges for two-seam mining of trona beds with interburden of 10 m (33 ft). The use of narrow yield pillars and wide spans is needed to maintain the resource recovery and productivity achieved in single-seam mining and to minimize the stresses transmitted between the seams. Good long-term stability must also be maintained to prevent subsidence over a large portion of the mine beneath the Green River.

The first issue, higher-than-gravity vertical stresses, became evident from repeated overcore stress determinations, which suggest a vertical stress gradient of 29 to 31 KPa/m (1.30 to 1.35 psi/ft) depth, which is about 30% to 40% greater than suggested by the density of the overburden alone. While not well understood, the high vertical stresses were adopted in the mine design to prevent possible stability problems.

The second issue, time-dependent stress transfer, came to light when planning the yield pillars. Overcoring measurements indicated

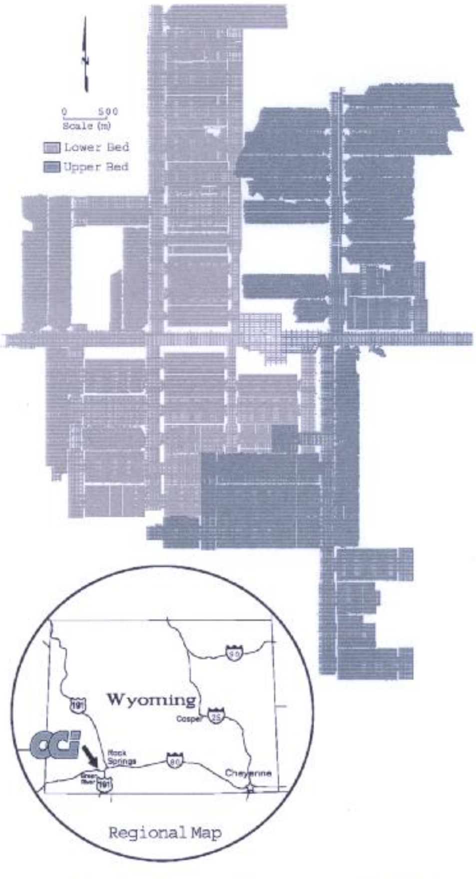


Figure 1. Location and Underground Map of OCI's Big Island Mine

that considerable stress transfer would occur in time causing large abutments, which need adequate barrier pillars for their support. Such stress transfer impacts schedules and mining sequences.

Finally, the third issue, stresses induced by strata gas, was recognized as a potential stability problem when gas pockets were first encountered early during mining operations. However, it was only recently that high-pressure gas was encountered of sufficient magnitude to potentially induce large roof falls. Although the use of roof gas pressure relief holes has been successful in preventing further large roof falls, a better understanding of the gas pressure and stress inducing mechanisms are needed.

The mine is located 40 km (18.6 miles) northwest of Green River, Wyoming. Mining operations supply trona, a sodium mineral, to the refinery for the production of soda ash. Figure 1 shows the location and the underground map of the mine. Room-and-pillar mining evolved from drilled-and-blasted square or nearly-square pillars to continuous machine-mined, thin, rectangular (yield) pillars. A chevron (fishbone) pillar layout was adopted to allow for the more efficient use of large continuous miners. Figure 2 shows typical good roof and rib conditions in a beltway-room chevron intersection.

Figure 2. Typical Good Roof, Floor, and Pillar Conditions in a Beltway-Room Intersection

The trona deposits in southwest Wyoming occur in the Wilkins Peak Member of the Green River Formation. The strata in the vicinity of the two trona seams are formed by beds of marlstone and shales containing thin oil shale beds. The immediate roof in both seams is formed by weak shale/mudstones with irregular dispersed trona. The overburden consists mostly of a series of thick siltstone, sandstone, and mudstone strata.

HIGHER-THAN-GRAVITY VERTICAL STRESSES

The Issue

Overcoring measurements at the Big Island Mine by the U.S. Bureau of Mines (USBM) (Aggson 1974, Bickel 1993) and Agapito Associates, Inc. (AAI) (Agapito and Hunter 1988) suggest a vertical stress gradient of at least 29 KPa/m (1.3 psi/ft) depth, which is 30% higher than the expected gravity gradient. Although the measurements fall within the scatter of relatively shallow measurements elsewhere (Hoek and Brown 1980), vertical stresses in sedimentary strata, such as that in the Green River Basin, are expected to be equal to those given by the weight of the overburden. This would result in gradients of 21 to 24 KPa/m (0.95 to 1.05 psi/ft) depth.

Measured horizontal stresses are slightly higher than vertical stresses, but for design purposes they are assumed to be equal. While the horizontal stresses are not sufficiently high to impact mine design, the high vertical gradient can be an important stability issue.

How Can High Vertical Stresses be Explained?

The existence of high vertical stresses in such a "benign" geologic environment is puzzling. A precise level survey between Little America and Granger showed that an uplift of 9.4 cm (3.7 inches) had occurred at the surface above the trona deposits in a 25-year span between 1958 and 1983 (Coyne and Brown 1992). Seismic reactivation of a suspected plug zone and "trona flowage" were advanced as possible causes of the uplift. Could such mechanisms induce upward forces on the mine floor and overburden? These mechanisms are highly speculative.

Maybe the excess gradient is due to time-dependent stress transfer from the mine workings, which is known to exist, and is considered a separate issue. Or maybe the high vertical stresses were due to consistent measurement error. A detailed evaluation and review of the measurements and overcoring technique have been made through the years. First, it was thought that plastic behavior of the trona may be one of the culprits. As an evaporite mineral, it was natural to consider the plastic behavior of trona to be similar to that of potash and salt. But early tests by the USBM (Obert 1965) showed that trona was mostly linearly elastic within the range of most mining stresses as opposed to the elasto-plastic behavior of potash and salt. Overcoring strain relief profiles always show a very stable curve with a flat base after the instrument strain buttons are overcored. Also, the biaxial testing of 15-cm-diameter (6-inch) core shows in most cases

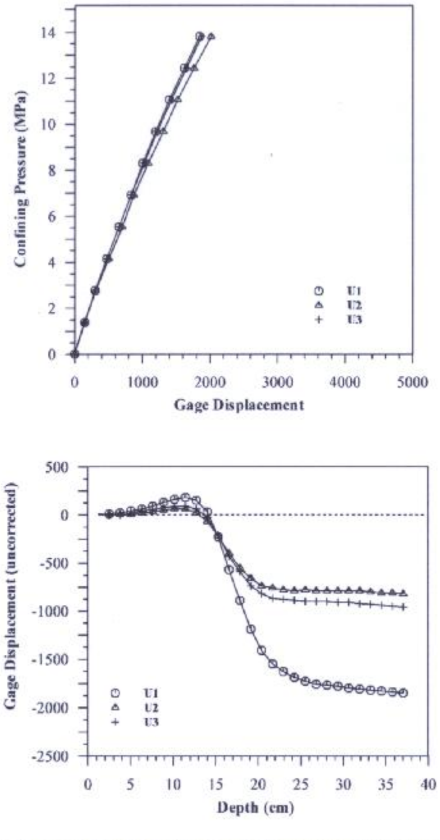


Figure 3. Typical Strain Relief and Pressure-deformation Curves

Figure 4. Agapito Associates, Inc. Overcoring CP-65 Drill Setup in a Trona Mine

a linear stress deformation curve with no or minimal hysteresis. Figure 3 shows such typical behavior.

Overcoring has been shown to be a reliable method for stress determinations for almost 50 years. AAI uses the borehole deformation gauge (BDG) and overcoring technique, developed by the USBM (Hooker and Bickel 1974, Hooker et al. 1974, Bickel 1985). Figure 4 shows a typical overcoring drill setup at a trona mine. The method and procedure followed is specified by the American Society for Testing Materials (ASTM) D4623. The same overcoring technique, equipment, and personnel have measured stress gradients in other areas of the Green River Basin and other regions of the United States where vertical stresses were found to be consistent with gravity loading.

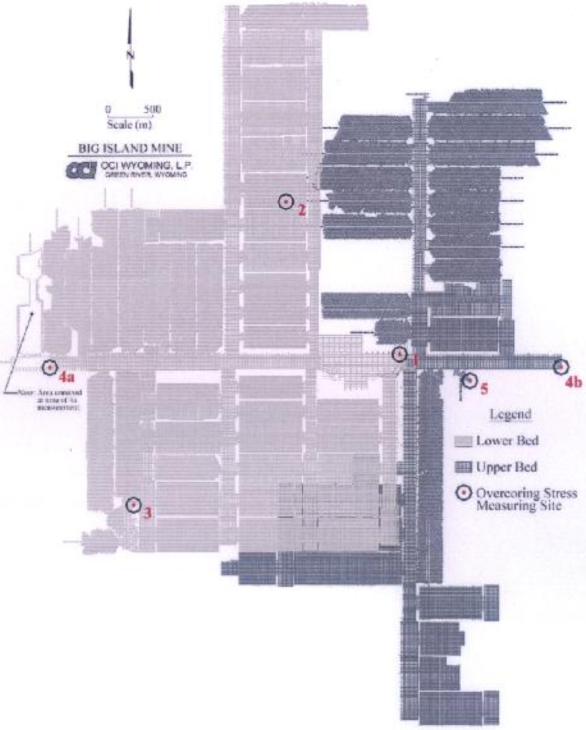
The accuracy of measurements and calculated stress is a function of a combination of various errors: errors in the BDG measurements, elastic modulus test, Poisson's ratio, axial stress, borehole diameter, and the assumed isotropy and linear elasticity of the rock. In the good quality trona of the Green River Basin, the measured accuracy is estimated to have an overall error of ±13%.

After the above brief discussion, we are left without conclusive explanation of the high vertical stress gradient.

Evidence of High Vertical Stresses

Figure 5 shows the overcore site locations and summarizes the vertical stress gradients calculated from the measurements. The first measurements at the Big Island Mine were performed by the USBM in 1974 (Aggson 1974). The measurements were made in the northeast corner of a panel with 6.7-m-wide (22-ft) entries and very large pillars of 57 m by 23 m (188 ft by 75 ft), which became the underground shop area (Figure 5, Site 1). The vertical stresses at a depth of 247 m (810 ft) were 7.6 MPa (1100 psi), indicating a vertical stress gradient of 31 KPa/m (1.36 psi/ft) depth. The high gradient was believed to be due to the overcore holes not being sufficiently deep to place the measurements outside the stress concentration zone around the opening. Time-dependent load transfer from such large pillars was thought to be unlikely to be the cause of the high gradient in the four months since the pillar had been mined.

In 1986 extensive pillar overcore measurements were made to determine the stress levels at which different sized pillars yielded (Figure 5, Site 2) (Agapito and Hunter 1988). An estimate of the vertical stress gradient was obtained by comparing the measured and calculated stresses. Measurements in other mines had shown that measured and calculated vertical stresses in stable, non-yielding pillars away from barriers or failed pillars were approximately equal. At the Big Island Mine measurement results from seven overcore holes were within a 3% difference between measured and calculated stresses when a 29 KPa/m (1.3 psi/ft) depth was used in the tributary area theory calculation.



Summary of Vertical Stress Gradients		
Site Location	Gradient (KPa/m)	Measurement Date
1	31	1974 (USBM)
2	29	1988 (AAI)
3	29	1998 (AAI)
4a	30	2000 (AAI)
4b	38	2000 (AAI)
5	31	2003 (AAI)

Figure 5. Location of Measurements and Summary of Vertical Stress Gradients

The high stress gradient was adopted for mine design after these measurements. This decision was made with a conservative perspective and a hope that future measurements would show a "normal" gravity load gradient. Using the high gradient in design can significantly change the extraction ratio results.

In the last five years, there were three other opportunities for more overcore measurements. The results summarized below confirmed the high gradient.

In 1998, measurements (Figure 5, Site 3) were made in a large block of trona near a large roof fall to investigate the existence of abnormal local stress conditions. The results showed stress levels comparable to other areas of the mine. Vertical stresses calculated by modeling using both a "normal" gravity load gradient of 25 KPa/m (1.1 psi/ft) depth and a high 29-KPa/m (1.3-psi/ft) depth gradient are shown in Figure 6, as well as the actual overcore results. The stresses calculated using a high gradient fit closely the measurement results.

In 2000, stress determinations were made to verify the two-seam design and validate the 29-KPa/m (1.3-psi/ft) depth gradient.

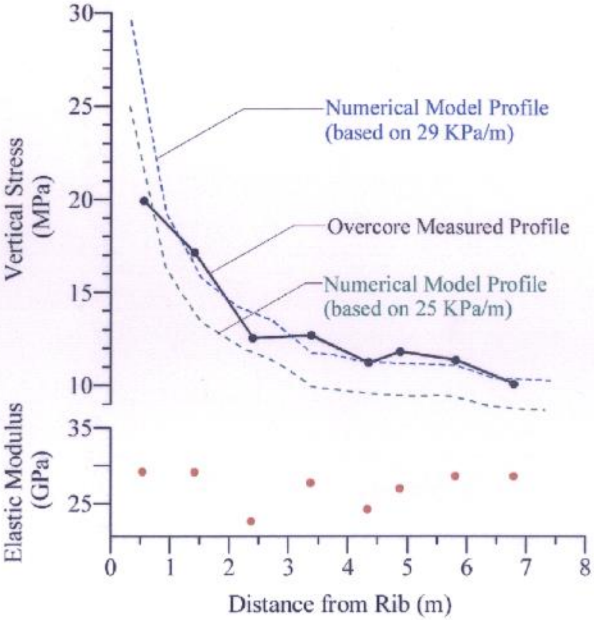


Figure 6. Comparison of Measured Versus Modeled Vertical Stress Profiles (1988)

Two sites were selected: one in the Lower Bed West (LBW) mains and the other in the Upper Bed East (UBE) mains (Figure 5, Sites 4a and 4b). The sites were selected in the western and eastern mine boundaries to minimize the influence of abutment loading from the production areas. Three mutually orthogonal holes were drilled at each site to obtain the three-dimensional stress state. Hole depth was about 17 m (55 ft) for the horizontal holes and 8 m (25 ft) for the vertical holes. The results showed significantly different gradients between both sites. While the LBW site, at 30 KPa/m (1.32 psi/ft) depth, is close to previous measurements, the UBE site, at 38 KPa/m (1.69 psi/ft) depth, is 28% higher. The measurements were closely checked, but no error was found to invalidate the results. A marked difference between the sites was the age of the workings. In the LBW site the measurements were performed four months after the openings were made and in the UBE site 22 years after. Thus, time-dependent load transfer was identified as a possibility for the high gradient in the east.

Finally in 2003, an 18 m (58 ft) deep horizontal overcore hole was drilled in the UBE area to validate the time-dependent stress transfer hypothesis as the cause of the 38-KPa/m (1.69-psi/ft) depth gradient. The site was located in a 4.5-m-wide (15-ft) heading, before the entry was widened to 9 m (30 ft) by second-pass mining. This was located 120 m (400 ft) from the UBE mains to minimize or prevent abutment loading (Figure 5, Site 5). The measurements were made within one month of mining the opening. Figure 7 shows, in more detail, the site and the vertical stresses profile. The vertical stresses remained approximately constant after a borehole depth of 12 m (38 ft) was reached. A vertical stress gradient of 31 KPa/m (1.35 psi/ft) depth was obtained, very close with those measured elsewhere in the mine. These measurements were considered very important because of their location and age of opening. They confirmed (1) that the 38-KPa/m (1.69-psi/ft) depth gradient, measured in 2000, was due to time-dependent load transfer from the large mains pillars, and (2) that the 29-KPa/m (1.3-psi/ft) depth gradient, albeit puzzling, seemed to be a feature of the local stress environment.

The horizontal stresses measured in all sites show a consistent range of magnitudes slightly higher than the vertical stresses. However, they are not sufficiently high to impact stability.

TIME-DEPENDENT STRESS TRANSFER

The Issue

Room-and-pillar mining at the Big Island Mine evolved through the years from drilled-and-blasted square, or nearly square, rigid pillars to machine-mined, thin, rectangular yield pillars. Time-dependent stress transfer was recognized as an issue when planning the use of yield pillars. Both short- and long-term stability was dependent on the use of adequate barrier pillars in both seams, pillar yielding without a significant loss of strength, development of stable stress arching, and prevention of high stress transfer between upper and lower seam panels in the two seams.

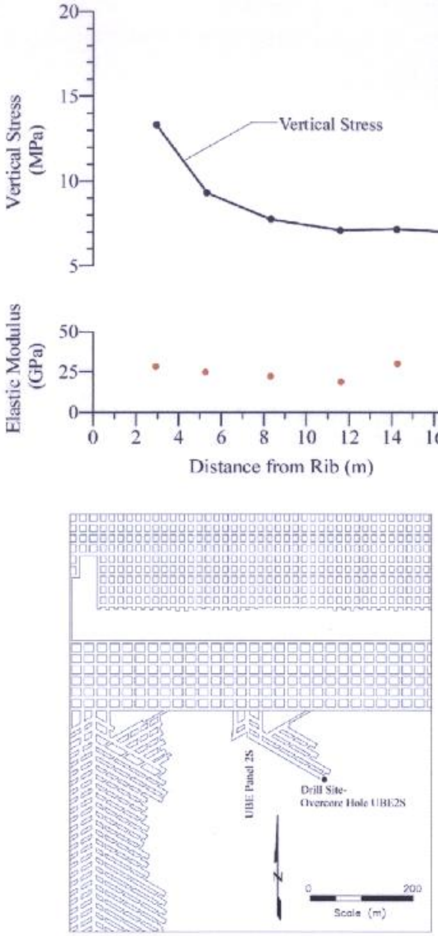


Figure 7. Location and Vertical Stress Profile (2003)

Stress Transfer from Thin Pillars

The development of the design to include the above factors was based on test mining, *in situ* instrumentation, and modeling (Gilbride et al. 2001, Agapito et al. 2000). A considerable amount of experience has been acquired with time-dependent ground response for single-seam mining, but two-seam mining has not yet begun.

Yield-pillar panels were developed on average 240 m (790 ft) wide and 800 to 1,600 m (2,625 to 5,250 ft) long with 20- to 30-m (65- to 100-ft) barrier pillars separating the panels. Yield pillars were mined in a chevron pattern 6.5 to 8 m (21 to 26 ft) wide separated by 9-m-wide (29-ft) rooms and 4.5-m-wide (15-ft) crosscuts.

Initial overcore measurements indicated that the yield pillars supported 75% of overburden loading 40 days after mining. Long-term stability was evaluated by determining time-dependent stress changes by computer modeling (Gilbride et al. 2001). Stresses predicted by modeling were checked by overcore measurements in two yield pillars and in a barrier pillar in one of the first full production panels (Figure 8). Measurements were made in 1997 and 2003, approximately 7 and 13 years after mining. Figure 8 shows the location of the measurements and compares the results with the 1990 modeling. In 1997, results indicated that pillar stresses were 10% to 20% higher and barrier pillar stresses 10% to 15% lower than predicted. In 2003 this difference remained about the same.

In comparing the 1997 and 2003 measurements, there was a decrease of 6% to 9% in the pillar stresses, but no increase in barrier pillar stresses as would be expected. Instead, a small decrease of 2% in barrier pillar stresses was measured. Although the changes in pillar stresses are within the instrument error, the results show a much earlier stability trend than in the 1990 analysis indicating smaller amounts of seam closure. A more refined three-dimensional analysis made in 2000 based on more recent measurements, shows a much closer agreement with the overcoring measurements (Figure 9).

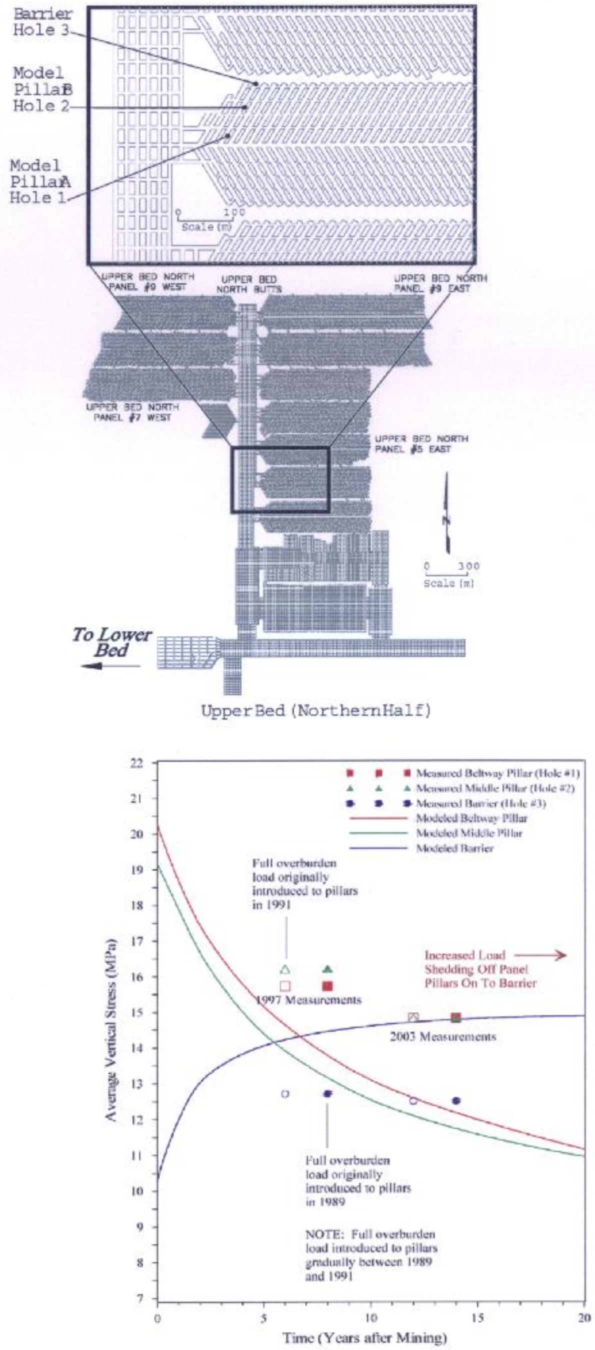


Figure 8. Location of Measurements and Comparison of Modeled (1980) and Measured Stresses (1997 and 2003)

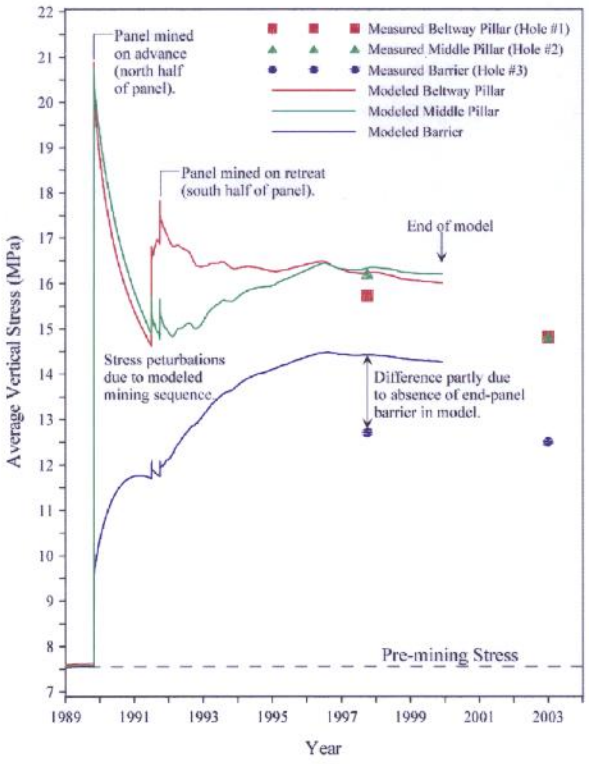


Figure 9. Comparison of Modeled (2003) and Measured Stresses (1997 and 2003)

Stress Transfer from Large Pillars

Measurements made in 1986 on an 11-m (36-ft) square pillar 8.5 months after mining, showed that there was only a 3% difference between measured and calculated stresses when a 29-KPa/m (1.3-psi/ft) depth gradient was used (Agapito and Hunter 1988). This was well within the measurement error, and it was concluded that the pillar was under full overburden load and had not yet shed load. Measurements made in 2000 at the end of the UBE mains indicated a 38-KPa/m (1.69-psi/ft) depth gradient as previously discussed. This high gradient raised concern that the planned two-seam design for the NE area was probably inadequate and may need to be modified. A three-dimensional creep model indicated that the high stresses were probably due to long-term stress transfer from the large 16-m by 20-m (52-ft by 64-ft) pillar in the mains. Figure 10 shows the model vertical stress profile. Stresses increase with time for a distance of 213 m (700 ft) indicating that significant stress transfer has occurred during 22 years. The 17-m-deep (55-ft) overcore holes were too short to reach past the abutment. At the time of overcoring the model stresses were 12% below the measured stresses.

The time-dependent stress transfer ahead of the UBE mains were supported by the 2003 overcoring measurements south of the mains (Figure 7) discussed in the previous section. In these measurements, a stress gradient of 31 KPa/m (1.35 psi/ft) depth was obtained consistent with other measurements elsewhere in the mine. The high 38-KPa/m (1.69-psi/ft) depth gradient measured in 2000 occurred in an abutment zone. Given enough time, load transfer can occur not only from thin panel pillars, but also from large mains pillars over a long distance. Thus, high stress conditions may be encountered when mining through these abutments at a later date. Reports of roof problems, when mining adjacent to old mined areas from other trona mines, may be due to this stress transfer mechanism.

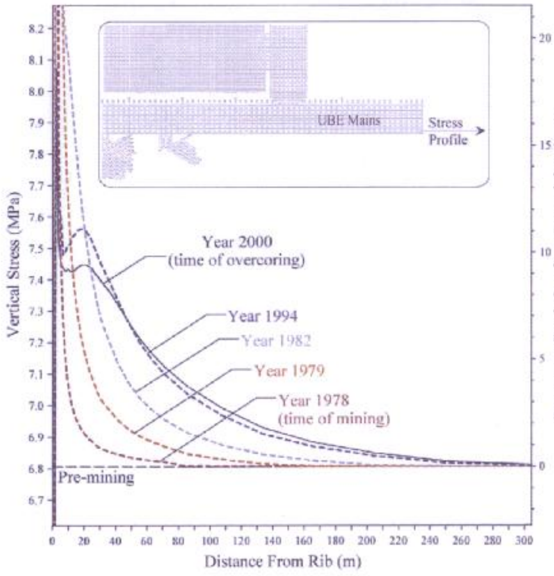


Figure 10. Modeled Vertical Stress Abutment Profile Ahead of UBE Mains

GAS STRESSES

The Issue

High-pressure gas pockets have been encountered in all local trona mines. These pressure have caused large roof falls. As a result, all the mine have resorted to drilling gas pressure relief holes in the roof, either routinely or on a spot basis, to prevent blowouts. A typical high-pressure gas release in the roof is shown in Figure 11. Although this procedure has greatly prevented roof falls, they can sometimes occur when other factors such as mining sequence, wide roof spans, local geologic weaknesses, etc., enhance the gas pressure effects.

Evaluation of Gas Pressures

Gas behavior is not well understood. A possible roof fall scenario involves (1) roof relaxation during mining, (2) concurrent increase in roof stress over newly formed pillars, (3) migration of gas from above pillars and openings to lower horizons near the roof, and (4) roof span deflection leading to the roof fall.

Gas was encountered in all holes in a recent bed-to-bed drilling program. Two of the holes were completed with casing and packers, and fitted with pressure gauges to measure the time-dependent build-up of gas pressure. Pressures, as high as 986 KPa (143 psi), were recorded during drilling. However, peak pressures, as high as 1380 KPa (200 psi) or more, were estimated to exist at some locations based on the response of the drilling equipment. The duration of high-pressure releases varied from seconds to several minutes. Such pressures can easily induce roof falls.

Figure 12 shows a large roof fall induced by gas pressure. The failure occurred in about four minutes from initial indications of instability to the actual fall. The fall was 3.4 m (11 ft) high with a smooth dome and flat roof shape as shown in the figure.

Figure 11. High-pressure Gas Emission from a Relief Hole in the Roof at OCI

Figure 12. Roof Fall Induced by Gas Pressure

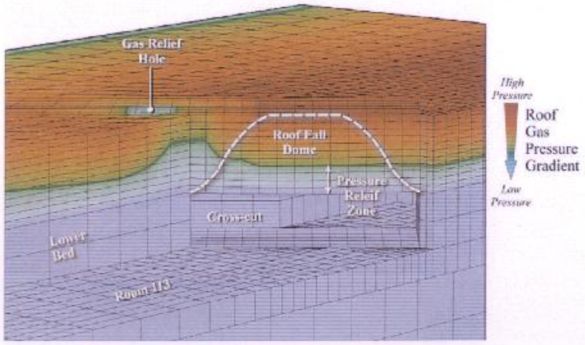


Figure 13. Modeled Roof Fall

A back analysis of the roof fall, where gas pressure was introduced in the model from a horizon 3.4 m (11 ft) above the roof, is shown in Figure 13. Failure in the model was prevented when a gas relief hole was located in the center of the intersection. This practice is now followed by OCI in all areas where high gas pressure is found.

CONCLUSIONS

In today's mineral markets, high resource recovery and low mining costs are needed in order to remain competitive. In underground mines, this is usually done by using increasingly larger equipment requiring larger openings spaced as closely as possible. This must be achieved without significant environmental damage to the surface and subsurface. In the case of OCI, this means no or negligible surface subsidence under the Green River.

The three stress issues discussed in this paper have the potential to affect mine stability and became more critical as the room-and-pillar method changed from a rigid to a yield pillar system with increased resource recovery and wider rooms. This potential is further accentuated in future two-seam mining.

Overcore stress determinations greatly helped define the first two issues. In the third issue, they helped establish that high field (rock) stresses were not associated with roof falls caused by high gas pressures.

The first issue, higher-than-gravity vertical stresses, is the more contentious and puzzling. There is no obvious explanation for the high vertical stresses or, indeed, full proof of their existence. It is possible that a systematic measurement error has been responsible for the high stresses measured through the years. However, this is unlikely because "normal" gravity gradients have been measured in other mines using the same equipment and personnel. The high gradient has been adopted in OCI mine design for almost 20 years to avoid the possibility of stability problems due to higher-than-gravity vertical stresses.

The second issue, time-dependent stress transfer, was recognized when designing the yield pillar system. Recent measurements indicate stress transfer from yield to barrier pillars to be decreasing with time sooner than predicted due to conservative modeling assumptions. Recently, a closer agreement between measured and modeled stresses has been achieved by using a three-dimensional analysis based on up-to-date measurements and mining experience. These data were used in the two-seam mine design scheduled to begin in the near future. Significant stress transfer has also been shown to occur from large mains pillars given enough time. This fact could have stability implications when mining in adjacent areas at a later date.

Finally, the third issue, gas stresses, has been recognized in all trona mines for a long time. Although the use of gas pressure relief holes has prevented many roof falls, a better understanding of the mechanisms and pressures involved is needed for future mine design optimization.

ACKNOWLEDGMENTS

The authors are indebted to OCI Wyoming, L.P. who commissioned the work and allowed publication of this paper. Special acknowledgements are given to Mr. Jim Barrix, Specialist Technician at AAI, for performing much of the overcore measurements.

REFERENCES

Agapito, J.F.T., R.R. Goodrich, and M.L. Andrews, 2000, "Two-seam Mining Stability at OCI's Big Island Trona Mine," Mining Engineering, Vol. 52, No.4, pp. 27-31.

Agapito, J.F.T. and R.V. Hunter, 1988, "Improvements in Resource Recovery at Stauffer's Big Island Mine," International Journal of Mining and Geological Engineering, 6:195–214.

Aggson, J.R., 1974, "Report on the Determination of In Situ Stress in the Stauffer Chemical Trona Mine, Green River, Wyoming," Unpublished USBM Report, April 8.

Bickel, D.L., 1985, "Overcoring Equipment and Techniques Used in Rock Stress Determination (An Update of IC 8618)," USBM Information Circular No. 9013.

Bickel, D.L., 1993, "Rock Stress Determinations from Overcoring—An Overview," USBM Bulletin 694.

Coyne, J. and L.D. Brown, 1992, "Surface Deformations in the Green River Basin," Institute for the Study of the Continents, Cornell University, Ithaca, NY.

Gilbride, L.J., J.F.T. Agapito, and K.F. Hollberg, 2001, "Time-dependent stability Implications for Planned Two-seam Mining at the OCI Wyoming, L.P., Big Island Trona Mine," Proceedings of the 38th U.S. Rock Mechanics Symposium, DC Rocks: Rock Mechanics in the National Interest, July.

Hoek, E. and E.T. Brown, 1980, Underground Excavations in Rock, Institution of Mining and Metallurgy, London.

Hooker, V.E. and D.L. Bicket, 1974, "Overcoring Equipment and Techniques Used in Rock Stress Determination," USBM Information Circular No. 8618.

Hooker, V.E. and J.R. Aggson, and D.L. Bickel, 1974, "Improvements in the Three-Component Borehole Deformation Gauge and Overcoring Techniques," USBM Report of Investigations No. 7894.

Obert, L., 1965 "Creep in Model Pillars," USBM Report of Investigations (RI 6703).