To be presented at
18th CONFERENCE ON GROUND CONTROL IN MINING
August 3-5, 1999

ROCK MECHANICS ISSUES IN THE TRONA PATCH

by
Archie M. Richardson
J. F. T. Agapito
Leo J. Gilbride

Agapito Associates, Inc.
Grand Junction, Colorado, USA

ABSTRACT

The trona mines in the Green River Basin, commonly known as the "trona patch," present an interesting set of rock mechanics issues stemming from mining in a unique underground environment. Like other minerals occurring in tabular deposits, trona is mined using high-productivity room-and-pillar and longwall methods. However, trona does not behave quite like other evaporites and behaves far differently than coal.

In this paper, the following key issues in trona patch rock mechanics are discussed: material properties, *in situ* stress field, water and gas pressure effects, creep characteristics, pillar behavior, roof span stability, floor stability, underground tailings storage, longwall mining, two-seam mining, and solution mining.

Many of the existing trona producers are entering potentially more difficult mining conditions, and much consideration is being given to "new" technologies such as longwall mining and solution mining. In analyzing 20 years of experience with trona patch rock mechanics issues, the authors have identified key comparisons and contrasts with conventional tabular deposit rock mechanics that will help illuminate what has been learned as the trona patch enters the 21st century.

INTRODUCTION

The region encompassing the trona deposits near Green River, in southwestern Wyoming, has come to be known in mining circles as the "trona patch" because it accounts for most of the North American production. Trona is an industrial mineral which is refined into soda ash, used in the manufacture of glass, fiberglass, and many other industrial and consumer products. Approximately 25% of the world's soda ash production comes from trona mined in the Green River Basin *(1)*. The trona is currently produced by five mines: (1) OCI Wyoming, L.P., (2) General Chemical Corporation, (3) Solvay Minerals, Inc., (4) Tg soda ash, inc., and (5) FMC Corporation (Figure 1). Four of these exclusively use room-and-pillar methods, while the fifth is primarily a longwall mine.

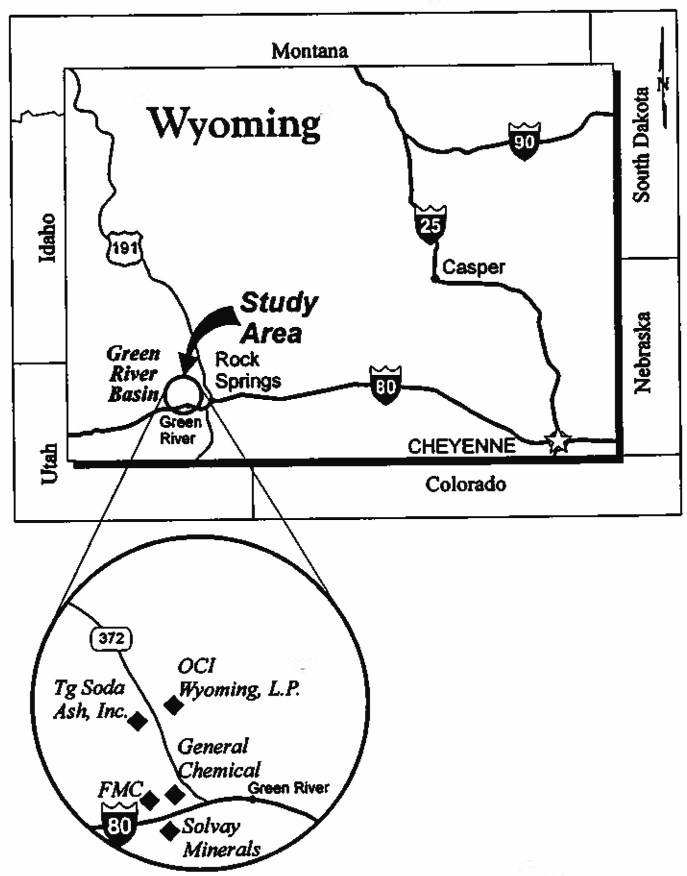

Figure 1. Location of Current Trona Mines in Green River, Wyoming, USA

This paper discusses rock mechanics issues in the trona patch, focusing on those unique to the extraction of trona in the Green River Basin.

MINING ENVIRONMENT

Geology

The Wilkins Peak Member of the Green River Formation contains approximately 25 important trona beds that represent deposits from evaporation of a large inland lake during Eocene time (Figure 2). These are numbered in stratigraphic sequence from the oldest (Bed 1). The most important beds currently being mined are Beds 17, 19, 20, 24, and 25. Bed 17 is the most productive to date, hosting the Solvay, FMC, and General Chemical operations. Tg is operating in Beds 19 and 20, while OCI mines Beds 24 and 25.

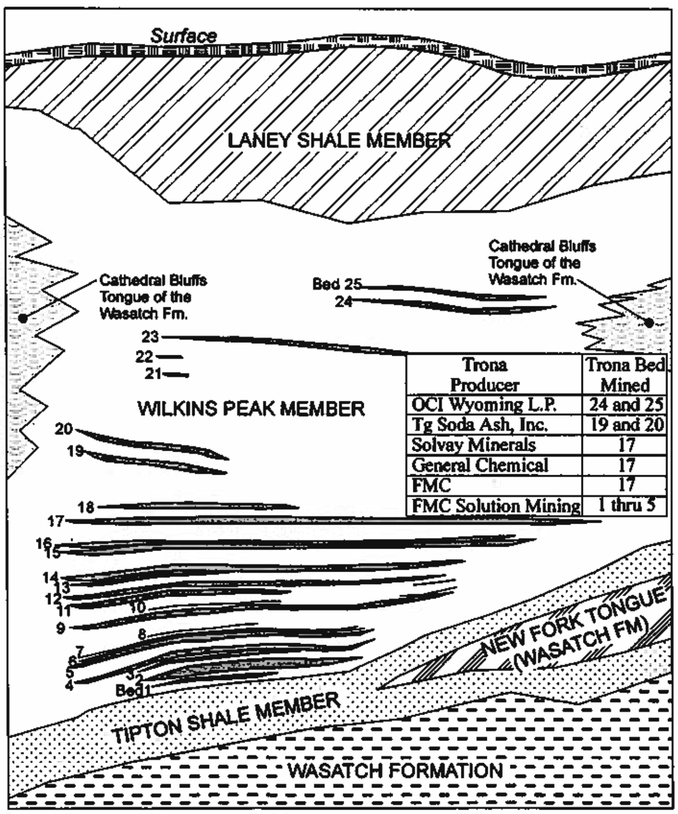

Figure 2. Generalized Geologic Column *(after 1)*

The trona occurs in a diverse bedded sequence that includes shales, oil shales, marlstones, sandstones, siltstones, limestones, and tuffs.

Material Properties

Trona is generally much stronger and stiffer than the immediate roof and floor rocks, with the degree of contrast varying with different beds and locations. Table 1 provides some typical values.

Table 1. Typical Nominal Values for Intact Rock Properties *(true values vary with bed and location)*

Horizon	Unconfined Compressive Strength (psi)	Elastic Modulus (psi)
Immediate Roof	6,000	1,000,000
Trona	8,000	3,000,000
Immediate Floor	4,000	500,000

Trona shows some time-dependent behavior, but few laboratory creep tests have been performed. Creep tests on model pillars *(2, 3)* show a much slower creep rate than salt. Much of the time-dependency exhibited in the field may in fact represent creep of weaker roof and floor strata rather than the trona bed itself.

Stress Environment

Repeated overcoring stress measurements by both the U.S. Bureau of Mines (USBM) *(4, 5, 6)* and Agapito Associates, Inc. (AAI) *(7) mostly* suggest a vertical stress gradient of 1.3 psi/ft depth and a horizontal:vertical stress ratio of approximately 1:1. Measured horizontal stresses are not sufficiently high to impact mine design; however, the high vertical stress gradient may be an issue.

Figure 3 shows close agreement between overcored vertical stress measurements in the rib of one room-and-pillar mine and a 1.3 psi/ft of depth vertical stress gradient. The model accounts for the stress effects induced by the local mining geometry and the stiffness of the roof, trona bed, and floor.

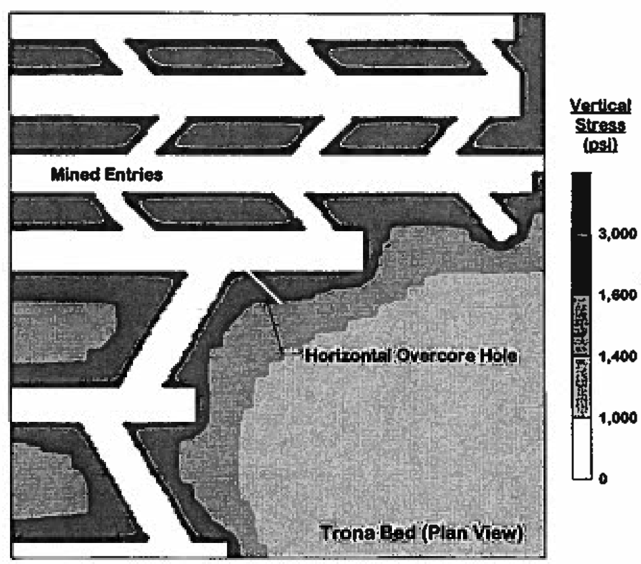

Figure 3a. Modeled Vertical Stresses at an Actual Overcore Stress Measurement Location, Based on a 1.3 psi/ft of Depth Vertical Stress Gradient

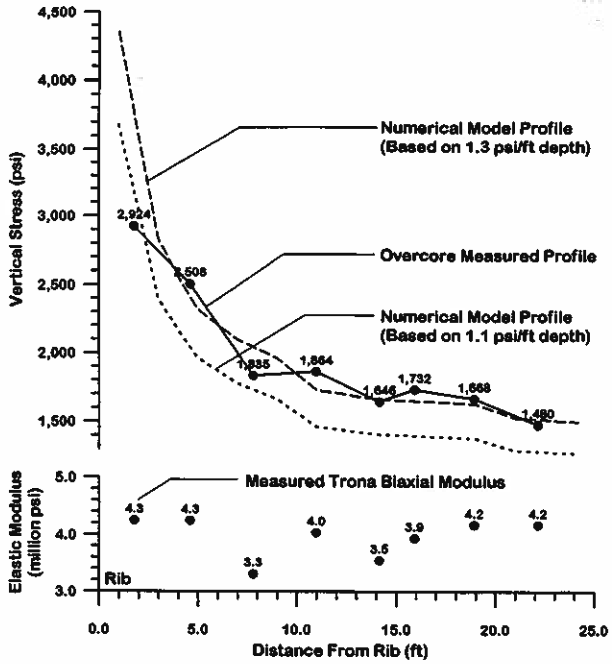

Figure 3b. Comparison of the Modeled versus Measured Vertical Stress Profile from Figure 3a

The back-calculated vertical stress gradient reflected in Figure 3b is somewhat higher than the 1.1 psi/ft calculated from gravity loading, although either fall within the scatter of relatively shallow vertical stress measurements elsewhere *(8)*. Using the higher stress gradient *can* significantly change the results of design analysis, where the objective is to optimize the extraction ratio in the presence of weak roof and floor strata. More research is needed to resolve uncertainties regarding the stress field. In the interest of conservative design practice, we believe the higher stress gradient should not be dismissed arbitrarily.

Although trona mines are often dry, water occurs in the floor at some locations. Water can have a weakening effect of up to 50% or more on both the trona and the roof and floor rocks. Methane, ammonia, and other gases occur in the trona formations, with methane particularly abundant in the associated oil shales. Gas under pressure has been reported at several operations. Weller *(9)* reports gas cavities in Bed 17 at Solvay up to 25 ft × 15 ft × 1 ft in dimensions that contained sufficient gas pressure to eject rocks up to several hundred feet when intersected by mining.

ROOM-AND-PILLAR MINING

Key elements of rock mechanics for room-and-pillar trona mining include behavior of:

1. Roof/pillar/floor system
2. Roof spans
3. Yield pillars
4. Barrier pillars
5. Roof support

Despite the abundance of attention given to design of stable pillars, few instances of actual pillar failures have been reported in the trona patch because of the aforementioned contrast between the strength of the trona and the surrounding rocks. Upon closer inspection, many cases of "pillar failure" turn out to be pillar *foundation* failures (Figure 4). This is not just an issue of semantics because designs based on pillar strength alone without considering punching mechanisms are inadequate, much like high-rise building designs that ignore the foundation loading.

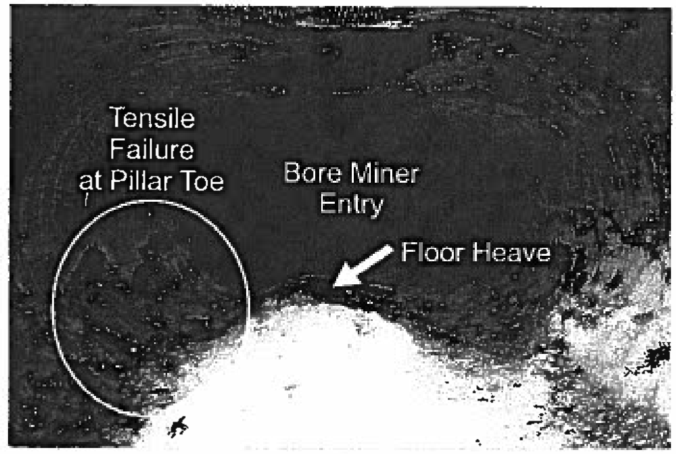

Figure 4a. Initial Rib Slabbing and Floor Heave in Response to Yielding of Pillar Foundation

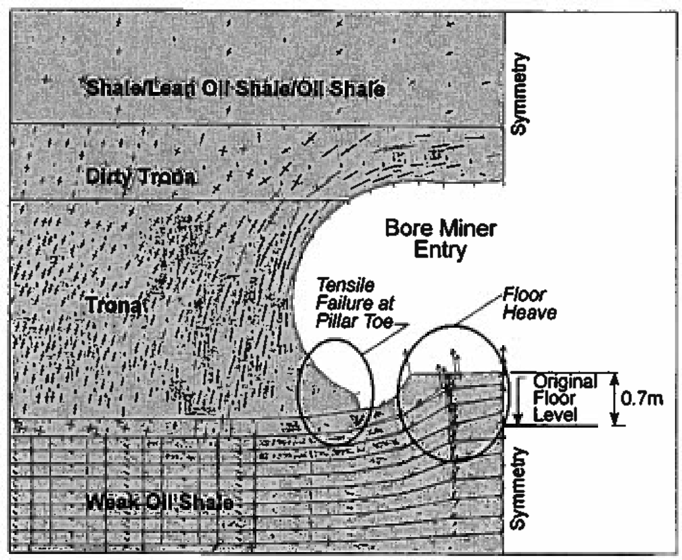

Figure 4b. Numerical Model of the Pillar Foundation Yielding Mechanism Pictured in Figure 4a *(above)*

The initial behavior shown in Figure 4 can ultimately result in pillar failure by progressive rib slabbing in response to tensile stresses induced by lateral deformation of the foundation strata, as shown in Figure 5. Loading of the weak roof and floor rocks can cause them to yield, weakening the pillar by developing tensile stresses in the trona. This behavior can be readily

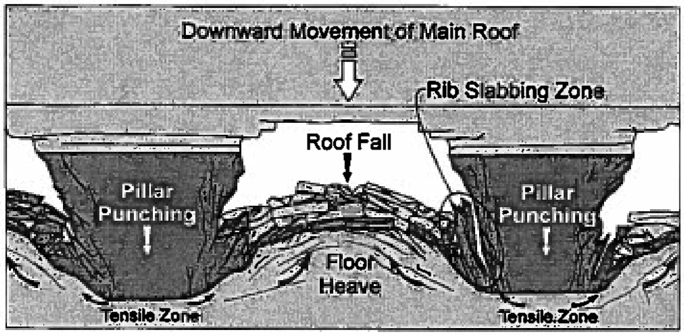

Figure 5. Ultimate Pillar and Roof Failure Resulting from Foundation Failure

demonstrated in the laboratory by placing a soft material in the specimen-platen interface prior to testing. Slabbing of the pillar edges is common even in conservatively sized rigid pillars and is not in itself an indication of instability. Further, core discing often occurs near the pillar edges, which is actually a manifestation of elastic pillar behavior.

Yield pillars are commonly employed in the mining industry to minimize floor heave and roof instability in areas subjected to high gravity or abutment loading. However, yield pillars in trona are problematic because of the characteristics of the roof/pillar/floor system. Rather than yielding by progressive rubblization like typical 30-ft-wide coal pillars, trona pillars remain relatively elastic (i.e., unyielding) even when they are quite thin (15-ft wide or less). Any yielding that does occur in the pillar is likely to be in the form of slabbing, which is difficult to control. If the pillar width is further decreased in an attempt to promote yielding, the stress ultimately becomes sufficient to result in foundation failure described previously *(10)*.

Pillar widths may be reduced somewhat to induce a limited amount of pillar/floor yield in a panel to optimize resource recovery *(7)*. Large arrays of thin pillars must be separated by barriers of sufficient width to isolate yield zones and promote stress transfer. Extraction ratios within the panel must be carefully selected, in some cases, to permit the panel to be completed before excessive closure limits access. Bore miners are particularly sensitive to this issue.

Roof span behavior in the trona patch is variable and depends on depth and local geology. Spans of 15 ft are common in Bed 17, and have been extended to 29 ft in the shallower cover conditions of Beds 24 and 25 with good success. Areas where pillar loading is high can result in "cutters" and increased risk of roof fallouts. This is particularly evident in Bed 20 where poor roof conditions are induced by yielding floor strata.

Smooth dome-shaped roof falls, some quite large, are sometimes initiated by high gas pressures in laminated roof strata (Figure 6). These tend to occur first in intersections where spans are greatest. A postulated mechanism involves (1) stress relief by roof relaxation above the intersection during mining; (2) concurrent increase in roof stress over the newly formed

Figure 6a. Smooth Dome-shaped Roof Fall Across Laminated Strata in an Intersection

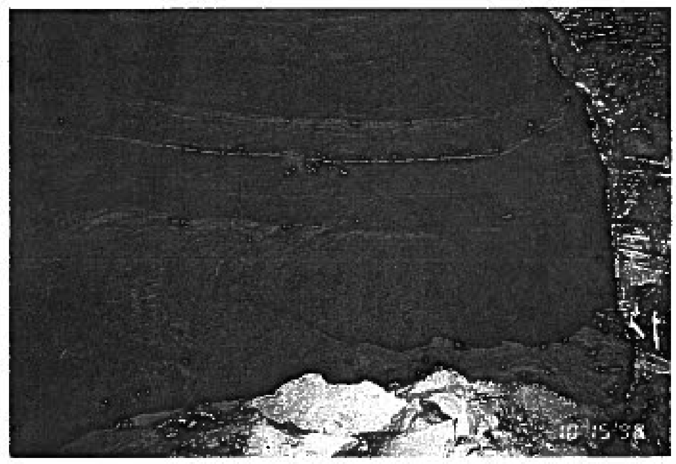

Figure 6b. View of Dome-shaped Roof Fall from Crosscut

pillars; (3) migration of gas down-gradient from above the pillars to the intersection roof; and (4) roof span deflection leading to ultimate failure from gas pressure, as shown in Figure 7. All of the mines have resorted to drilling gas pressure relief holes in the roof, either routinely or on a spot basis, to prevent blowouts.

Typical primary roof support in the trona patch consists of 5- to 8-ft fully-grouted resin bolts on 2- to 5-ft centers. One shallow operator uses 54-inch mechanical anchor bolts instead with historical success. Bolts alone are generally sufficient to maintain good roof conditions. Occasionally mats or mesh are supplemented on a local basis. Rarely is more substantial support required, except in Bed 20 where particularly poor roof conditions are induced by yielding floor strata. Under these circumstances, heavy ground support consisting of grouted bolts on 1-ft row spacing, cable bolts (up to 20-ft long), cable slings, and mats is oftentimes required to control the roof (Figure 8).

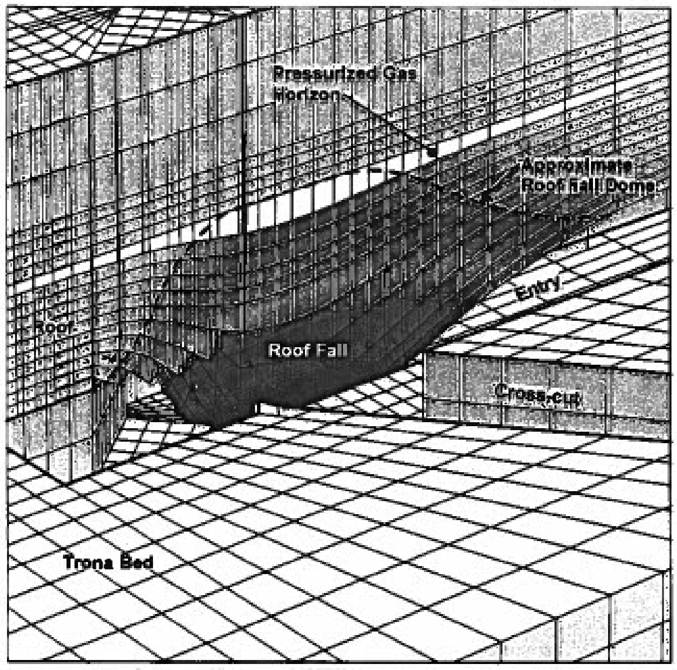

Figure 7. Numerical Model of the Domed Fall Initiated by Gas Pressure in the Roof Pictured in Figure 6

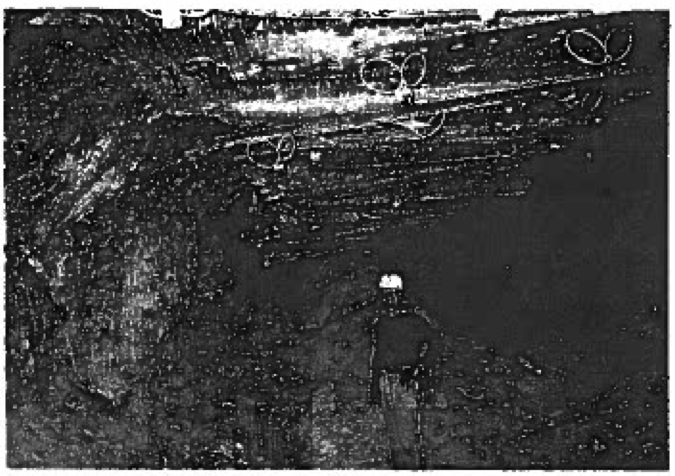

Figure 8. Heavy Roof Support Required Where Pillar/Rib Stresses Exceed the Strength of the Floor Strata *(note the use of cable bolts with head safety loops, mats, and cable slings)*

LONGWALL/SHORTWALL MINING

To date, two local operators have had experience with longwall mining of trona, both in Bed 17 *(11, 12)*, and one has employed shortwall mining in Bed 20 *(13)*. The first longwall was installed at General Chemical at a cover depth of 1600 ft. Many equipment-related problems were encountered due to the inadequacy of the contemporary longwall equipment, which was designed for cutting coal. Perhaps the primary rock mechanics problem was slabbing at the face. The larger slabs were 18-inches thick and up to 15-ft long, requiring secondary fragmentation prior to belt haulage. Other geotechnical issues included poor caving resulting in high abutment stresses leading to floor heave, and stress-induced fracturing and water inflow at the face. The longwall method was abandoned in the late 1970s.

Tg experimented with shortwall mining starting in 1982. The face support line consisted of 34 Dowty four-legged shields with a 660-T yield capacity (Figure 9). Extendable forepoles and a 5.5-ft stroke on the advancing rams allowed an 11-ft advance of the support tips. The last-used face length was 184 ft. Several ground control difficulties were encountered in the first panels. These included stress relief instabilities requiring heavy support in the tailgates and in development areas within the abutment zone of previously-mined panels. Average closure rates of 3 inches per day or more were reported in the front abutment area, requiring frequent cleaning of the floors. Floor heave experienced in early tailgates resulted in nonparallel roof and floor lines that created severe deformation in the shield bases and lemniscate links after repeated setting. Shortwall mining was discontinued in the mid-1990s.

Figure 9. Tg Shortwall Face Supported by 660-T Dowty Four-legged Shields

FMC started longwall mining in 1981, essentially contemporaneous with termination of the longwall experiment at General Chemical. Today FMC successfully operates the only non-coal longwall in the western hemisphere. Progress was slow in the initial panels, with productivity limited by slabbing at the face and slow cutting rates of the shearer, which was designed for cutting coal. Steady improvements in layouts, equipment, and operating practice that have come with experience have resulted in production rates as high as 5300 TPS *(12)*. In their quest for longwall success, FMC was aided by improvements in durability of equipment such as longwall shearers, but their own innovations were crucial. These included a specialized shearer drum and other equipment modifications.

From a ground control perspective there are several important lessons to be learned from these experiences: (1) floor heave from abutment loading is a major problem in longwall and shortwall gateroads and can only be controlled by large rigid pillars—yield pillars do not provide controlled entry closure; (2) in beds with an exceptionally sensitive floor, large barriers may be required to completely separate active panels from abutment zones from previous panels; and (3) where bore miners can be used, superior ground control is achieved.

CURRENT ISSUES

Longwall Mining

The success of FMC in Bed 17 has inspired other operators to look at longwall mining. We see no reason why longwall mining cannot be successful in other beds providing (1) subsidence can be tolerated, (2) the resource is sufficient for longwall panels, and (3) the roof and floor rocks have sufficient strength for efficient layouts.

More Difficult Conditions

It is likely that much of the resource will be more difficult to mine using mechanical mining techniques because of insufficient bed height, soft floor conditions, or depth. More difficult conditions have also been reported near the margins of individual beds because of dessication structures, gas, and other geologic features. Estimates of 500 years of production commonly cited *(1)*, based on reserve estimates and current production rates, may be optimistic.

Depth

Although economic reserves exist in Beds 12 and 14, and possibly others below Bed 17 *(1)*, trona has not been mined conventionally deeper than 1800 ft. Additional stress-related problems are expected at a depth of 2000 ft where a typical 50% extraction ratio produces an average pillar stress level of 5200 psi. A 5200-psi bearing stress is likely to exceed the strength of the pillar foundation in many of the beds. While there is substantial resource at shallower depths, future extraction of deeper beds is not expected to be economical with conventional mining techniques and will require more innovative methods, such as solution mining. FMC currently operates a solution mine pilot facility extracting brines from Beds 1 through 5 *(14)*.

Multi-seam Mining

The existence of 25 important trona beds makes it a certainty that multi-seam mining will be required in the future. Beds 12, 14, and 19 contain economic reserves directly below some existing working in Beds 17 and 20 *(1)*. To date there has been very limited experience with multi-seam mining of trona *(15, 16)*. OCI has experience mining two overlying panels 35 ft apart in Beds 24 and 25 at less than 850 ft of depth. Indications from the OCI experience are that multi-seam mining is possible *(17)*. As operating depths deepen, multi-seam mining will required added attention to panel alignment and sequencing, and provisions for increased ground support.

Underground Tailings Storage

Underground tailings storage is practiced at four of the five trona mines because of its long-term cost savings and environmental advantages. FMC and Tg both use non-managed placement systems that inject tailings directly into unmined workings from surface holes *(18)*. Solvay and OCI use managed systems where low-water-content slurries are delivered via a pipeline from surface and through the mine to abandoned panels. Dams are used to control placement and decant water from settled tailings. OCI returns approximately 90% of tailings underground. In considering the long-term effects of the method, the weakening effect of water on trona measure rocks previously mentioned should be considered in the design of underground tailings storage areas, especially if subsidence is a concern. Subsidence monitoring should be established to assure performance.

Continuous Miner versus Bore Miner Entries

Bore miners are being used successfully at two trona mines in conjunction with the more common ripper-type continuous mining machines used by all five operators. The ovaloid-shaped entry produced with the bore miner has proven to be intrinsically more stable than the conventional rectangular opening produced with the ripper miner, principally by virtue of its rounder shape. This is illustrated in Figure 10, which compares the rock yield zone surrounding both types of entry shapes for equivalent entry dimensions and the same pre-mining stress state. The figure shows considerably more yielding in the roof and floor with the rectangular opening. The smaller yield zone shown for the ovaloid opening is borne out in practice in the form of more stable roof conditions, reduced floor heave, and less rib slabbing. At FMC, the dramatically superior entry stability realized with the bore miner versus the ripper miner allowed the primary and secondary longwall gateroad support systems to be streamlined, resulting in reduced costs and increased productivity *(12)*. As mining conditions advance to greater depths and multi-seam mining becomes more prevalent, the inherent ground control advantages of the ovaloid entry must be weighed against the disadvantages of the bore miner, including the increased likelihood of becoming trapped in squeezing ground and the inability to regulate cutting height in response to changes in bed thickness.

SUMMARY

Ground response to mining in the trona patch is quite different from other evaporite deposits and coal. This is due to unique trona material properties, its higher strength in relation to roof and floor strata, and the geological environment.

More difficult mining conditions are anticipated in the future due to increased depths and geological features near the margins of the beds. The homogeneity in dips, bed thicknesses, and near-perfect ground conditions anticipated in the 1960s did not materialize, and ground control problems have occurred in some areas of all the mines. Estimates of several hundred years of production at current rates seem optimistic.

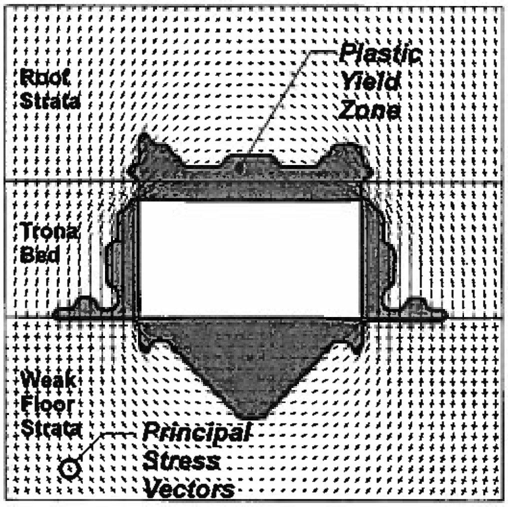

Figure 10a. Extent of Yield Zone Around a Rectangular Continuous Miner Entry

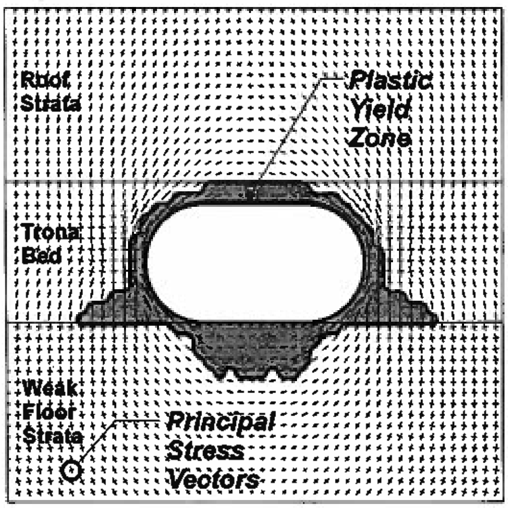

Figure 10b. Extent of Yield Zone Around an Ovaloid Bore Miner Entry

Room-and-pillar mining has been used efficiently to extract most of the trona to the present. However, it is likely that longwall mining will be used more efficiently in the future to achieve better productivity and resource recovery at depth. Solution mining offers the possibility to allow extraction in deeper and thinner beds and compliments the other mining methods.

REFERENCES

1. Brown, N. A. (1995), "Union Pacific Instrumental in Developing Wyoming Trona," *Mining Engineering,* February, 135–141.

2. Obert, L. (1964), "Deformational Behavior of Model Pillars Made from Salt, Trona, and Potash Ore." Proceedings 6th Symposium on Rock Mechanics, University of Missouri, Rolla, 539–560, October.

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

4. Morgan, T. A., W. G. Fischer, and W. J. Sturgis (1965), "Distribution of Stress in the Westvaco Trona Mine, Westvaco, Wyo.," USBM Report of Investigations (RI 6675).

5. 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.

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

7. 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.

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

9. Weller, M. (1998), "The Anomalous Zone in Bed 17," Proceedings of the 1st International Soda Ash Conference—Volume II, 33–36.

10. Maleki, H. and P. Hynes (1991), "Application of Microcomputers to Geotechnical Design and Stability Monitoring—A Case Study of Resource Recovery Optimization at the Tg Soda Ash Trona Mine," Longwall USA, Pittsburg, PA, June.

11. Dewey, J. R. and J. P. Aman (1976), "Longwall Mining of Trona," *Mining Congress Journal,* December.

12. Steenberg, R. L. and T. J. Davis (1998), "High Speed Cutting in Hard Seams: Evolution of Longwall Mining in Trona," Longwall USA Conference Proceedings, June 9–11, 175–194.

13. Hynes, P. W. (1989), "Shortwall Mining of Trona Using an Advancing Tailgate," *Mining Engineering,* November, 1126–1132.

14. Leigh, R. T. (1998), "Wyoming Trona: An Overview of the Geology," Proceedings of the 1st International Soda Ash Conference—Volume II, 1–14.

15. 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, Nevada, May 1–3, 57–64.

16. Kneisley, R. O. (1982), "Rock Mechanics Investigation of Two-Bed Trona Mining, Green River, Wyo.," USBM Report of Investigations (RI 8598).

17. Agapito, J. F. T., R. R. Goodrich, and M. L. Andrews (1999), "Long-Term Stability for Two-Seam Mining at OCI's Big Island Mine," Proceedings of SME Annual Meeting, Denver, CO, March 1–3.

18. Scriven, D. H. (1998), "Tailings Disposal Methods," Proceedings of the 1st International Soda Ash Conference—Volume II, 201–204.