APPLICATION OF TOMOGRAPHIC METHODS FOR STUDY OF STRUCTURAL FAILURE

By H. Maleki[1]

ABSTRACT

U.S. Bureau of Mines researchers investigated the principles, limitations, and application of tomographic measurements for monitoring the history of strata fracturing and failure. These measurements were complemented by static measurements, core testing, fracture mapping, and underground observations to relate measured changes in velocity patterns to the formation of fracture zones, changes in stress, structural stability, and secondary support requirements.

These measurements provided new insight into the mechanism of time-dependent failure and excavation-induced rock damage. It was shown that rock damage occurred at the development stage and was influenced by floor and pillar behavior. Tomographic methods clearly identified the development of damaged zones in the mine roof even though there was no visual indication of fracturing at the excavation surface. Fractures initially formed on one side of the roof but later propagated to the other sides, forming a block. In addition, significant changes in velocity in the pillar were measured and related to load transfer from mined-out areas to the pillar.

INTRODUCTION

Mining results in a redistribution of stresses around mine openings and the formation of fractures. These fractures are not of great concern unless they grow to intersect other potential failure zones and fail suddenly. However, gradual failure of rocks and ore is easily controlled by timely scaling, cleaning, and bolting.

On the other hand, sudden failure of rocks and coal involving over 100 t of material influences access to mine openings, compromises safety, and increases mining costs. Measurements in underground mines (Maleki, 1988) have shown that these failures are not instantaneous and generally take between 1 day to several years before the material actually collapses. These time-dependent failures are influenced by limited deformation of geologic material, changes in geologic conditions, effectiveness of support systems, and groundwater conditions, among other causes.

Sudden and violent failure of material around mine excavations are called bumps or bursts. These failures are common in both deep coal mines and hard-rock mines and require large-scale remedial actions.

The U.S. Bureau of Mines (USBM) has long been involved in the development of measurement techniques for assessing ground conditions and guidelines for detecting "sudden failures" in U.S. mines (Maleki, 1994). Recently, the author studied violent failures in U.S. coal mines and proposed an engineering approach for assessing bump-prone conditions (Maleki, 1995). In this approach, potential bump-prone areas may be identified using measurements of stress, considerations of the stiffness of surrounding rocks, and energy release from breakage of strata. Once an area is identified as bump prone, both static and geophysical measurements are recommended as a means of predicting where coal bumps will occur.

Among monitoring techniques, geophysical measurement methods are widely used in the study of coal bumps

[1]Mining engineer, Spokane Research Center, U.S. Bureau of Mines, Spokane, WA.

and rock bursts because they can be used to monitor large areas. These methods use either an active source, such as a blasting cap, to generate a signal or involve listening to rock noise. An active source is generally used in tomography to construct velocity and/or amplitude patterns in the area of interest. Microseismic methods, on the other hand, simply monitor seismic emissions, evaluate the energy involved, and locate rock noises.

Tomography provides some new capabilities for predicting violent failure. By conducting periodic surveys, one can identify abnormal geologic conditions during the early stages of mining; this finding would enable an operator to focus on remedial actions where changes in geologic conditions occur. Also, by repeating measurements at the location of interest, one can monitor changes in wave properties and infer the development of fractures (Maleki and others, 1993), yield zones (Maleki, 1995), and areas of high stress during later mining, which would permit timely assessment of the likelihood of violent failures.

The focus of this paper is on applying tomography to the study of rock fracturing, stress change, and failure. To achieve this goal, an extensive measurement program, consisting of both geophysical and static measurements, was implemented in an underground mine. Static measurements and borehole observations were used to relate changes in seismic velocity to strata fracturing and the failure process; these measurements resulted in a better understanding of the initiation and growth of failure zones around mine openings.

TOMOGRAPHIC METHODS

Tomography is an inversion technique that provides an image of a physical property of a solid material on a plane of interest. The word tomography is derived from the Greek word "tomos", meaning "a slice." Three-dimensional images can be obtained by repeating measurements along multiple planes (slices) and combining the two-dimensional images to create a three-dimensional image. Physical property measurements are obtained remotely.

Tomography was first applied in the medical industry as computer-assisted tomography (CAT) or computed tomography (CT) scans. There is extensive literature on the physics, mathematics, and design of CT scanners (Brooks and DiChiro, 1976). Briefly, CT rotates an X-ray source at least 180° around the object of study (human brain, etc.), causing the X-rays to intersect the object with numerous waves and create an image at several positions along the object. A three-dimensional image can be reconstructed from these sequential images as the object is moved through the scanner. CT scanners use X-ray attenuation and create images through computer manipulation of data. Contrast resolution is excellent. The scans are then viewed by trained personnel who identify abnormal conditions within the object.

During the last decade, tomography has also been widely used in studies of the physics of the earth and has advanced rapidly as a result of significant improvements in data acquisition methods, imaging theory, and computation speeds. Recently, the USBM applied this technology to ground control problems (Maleki and others, 1992, 1993; Maleki, 1994; Westman, 1993) and environmental research (Jessop and others, 1992).

Figure 1 presents the lithology of a typical mine roof and the location of sources and receivers around an area of interest. At such a mine, both variations in roof lithology near a sandstone channel and time-dependent strata separation contribute to roof falls. To conduct a tomographic survey, a number of sources and receivers are attached around the boundaries of the area of interest. Each source is excited, and the full waveform is recorded at all receivers. By then exciting other sources, the area of interest is intersected by a number of waves, resulting in a pattern of spatial variations of rock properties within the image zone. For example, by picking first-arrival times and using inverse methods, one can construct a wave velocity image of the mine roof. Similarly, an attenuation image may be constructed using wave amplitude.

Tomographic surveys have limitations influenced by (1) physical access to the area of interest and (2) nonlinear travel paths. Lack of access to all sides of an area (figure 2*A*) results in poor ray coverage in the upper portion of the roof. In contrast, figure 2*B* presents good ray coverage for a pillar survey where there is sufficient access from all four sides of the pillar. Nonlinear travel paths for elastic waves are influenced by contrasts in material properties. X-rays travel along straight lines, without the spreading and diffraction characteristics associated with elastic waves.

INSTRUMENTATION PROGRAM

Velocity tomographic surveys were conducted at high resolutions in a Western U.S. trona mine to study velocity patterns in the mine roof, pillar, and floor. Figures 3 and 4 illustrate instrument layout and the location of impact sources and receivers for the roof and floor surveys, as well as the positions of multipoint extensometers in the mine roof. Both a bolt-impulse source and seismic caps were used in this study.

These measurements were complemented by detailed deformation measurements, stress measurements, fracture mapping, and photographic records to relate changes in the velocity pattern to strata fracturing, stress build-up, structural stability, and supplementary support requirements. Static measurements were taken with 13 multipoint roof extensometers, 5 vibrating wire stressmeters, 5 rib dilation pins, 5 floor dilation pins, and 2 pillar convergence pins and provided a detailed history of strata deformation toward the entry. In addition, borehole shear tests, plate-bearing tests, and overcore stress measurements were obtained to measure the in situ strength properties of the rock strata. The instruments were installed in a four-entry panel access using 5-m (17-ft) wide entries and pillars at depths of 426 m (1,400 ft).

The tomographic surveys were completed on a biweekly to bimonthly schedule, depending on face position and rate of change in strata fracturing. Some static measurements were obtained either at the beginning or the end of the monitoring program. Other measurements were obtained on a daily to weekly basis. Systematic fracture mapping was also completed during each tomographic survey. Monitoring was continued until the retreat face approached the instrumented area.

TOMOGRAPHIC IMAGES AND GROUND CONDITIONS

The application of tomographic imaging to the study of strata fracturing and failure is demonstrated by using selected images from several time windows during the measurement program. Static measurements, numerical modeling, fracture mapping, and underground observations were used to develop schematics of roof and floor deformation and failure history. Selected pillar images were included to show how the method was used for monitoring stress changes in mine structures.

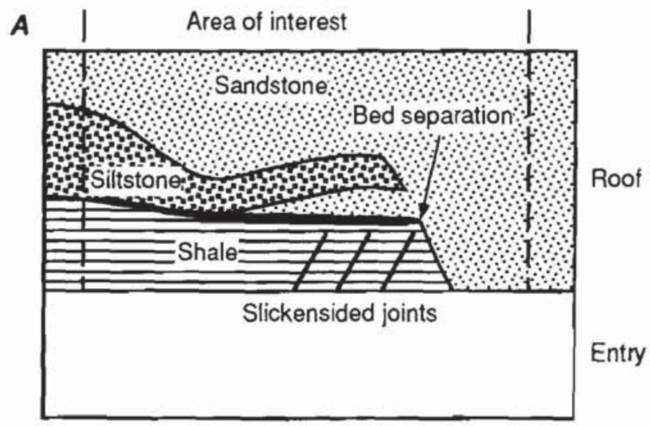
Wave velocity images for the mine roof and floor at the development face position (figure 5) have provided new insights into the mechanics of rock fracturing and damage, e.g., roof velocity was significantly lower near the pillar side than the solid block side. This significant change over a distance of 4 m (14 ft) was influenced by the composite behavior of the pillar and floor and associated shear fracturing (Maleki and others, 1993). This is an important finding because it confirms that damage to the rock mass is initiated during the development phase, while "sudden" failures may occur several months to years after mining. These measurements also identified the shortcomings of observational techniques for assessing ground conditions, because there was no sign of fracturing on the skin of the roof (figure 5*B*).

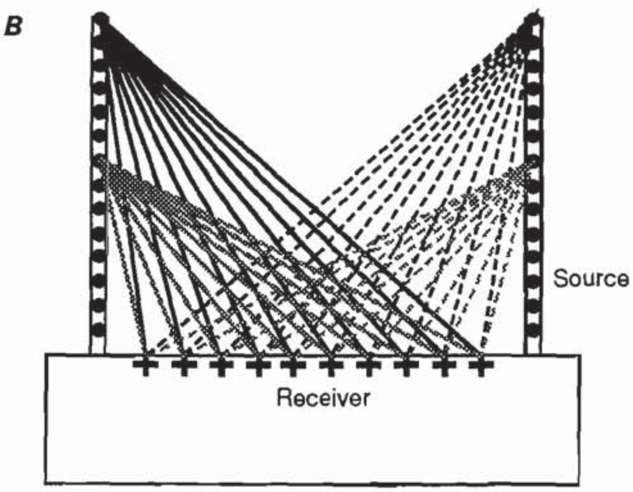
Wave velocity patterns in the mine floor showed a similar trend, but the magnitude of deformation, fracturing, and rock damage was higher than wave magnitudes in the mine roof. This pattern was based on observations of floor heave, fracturing, borehole inspection, and the velocity images. The large difference between roof and floor velocities was also influenced by lithologic differences between the roof and the floor material. Laboratory velocity measurements on intact core samples from both roof and floor, however, confirmed that excavation-induced rock damage was significantly greater for floor rocks. In fact, the premature failure of floor rocks contributed to the fracturing of the mine roof (Maleki and others, 1993).

Wave velocity in the mine roof changed significantly (25 pct) during this 6-month monitoring period as damage to the rock mass increased because of the growth of fractures and increases in bed separations. Figure 6 illustrates the velocity pattern and ground conditions when the retreating face approached within 15 m (50 ft) of the instruments. Initially, the roof behaved like a cantilever beam as rock fracturing developed toward the pillar side. In time, other fractures formed in the upper portion of the roof (near the solid block), forming a block of rock that was suspended from the upper strata by additional roof bolts. The operator installed sets of secondary support [wire mesh and 2.4-m (8-ft) long bolts] and tertiary support [3.6-m (12-ft) long bolts] to control block movements.

Wave velocity pattern was generally uniform, as measured in a 5.5- by 8.5-m (17- by 30-ft) portion of a mine pillar prior to the retreat of the mechanized face equipment (figure 7*A*). Velocities increased across the pillar as the face retreated toward the pillar, transferring stresses from the mined-out areas toward the pillar (figure 7*B*). At the time of the last measurement, the face-pillar distance was 15 m (50 ft). These measurements are in general agreement with the stress measurements and confirm that tomographic measurements are suitable for monitoring changes in stress conditions in mine structures.

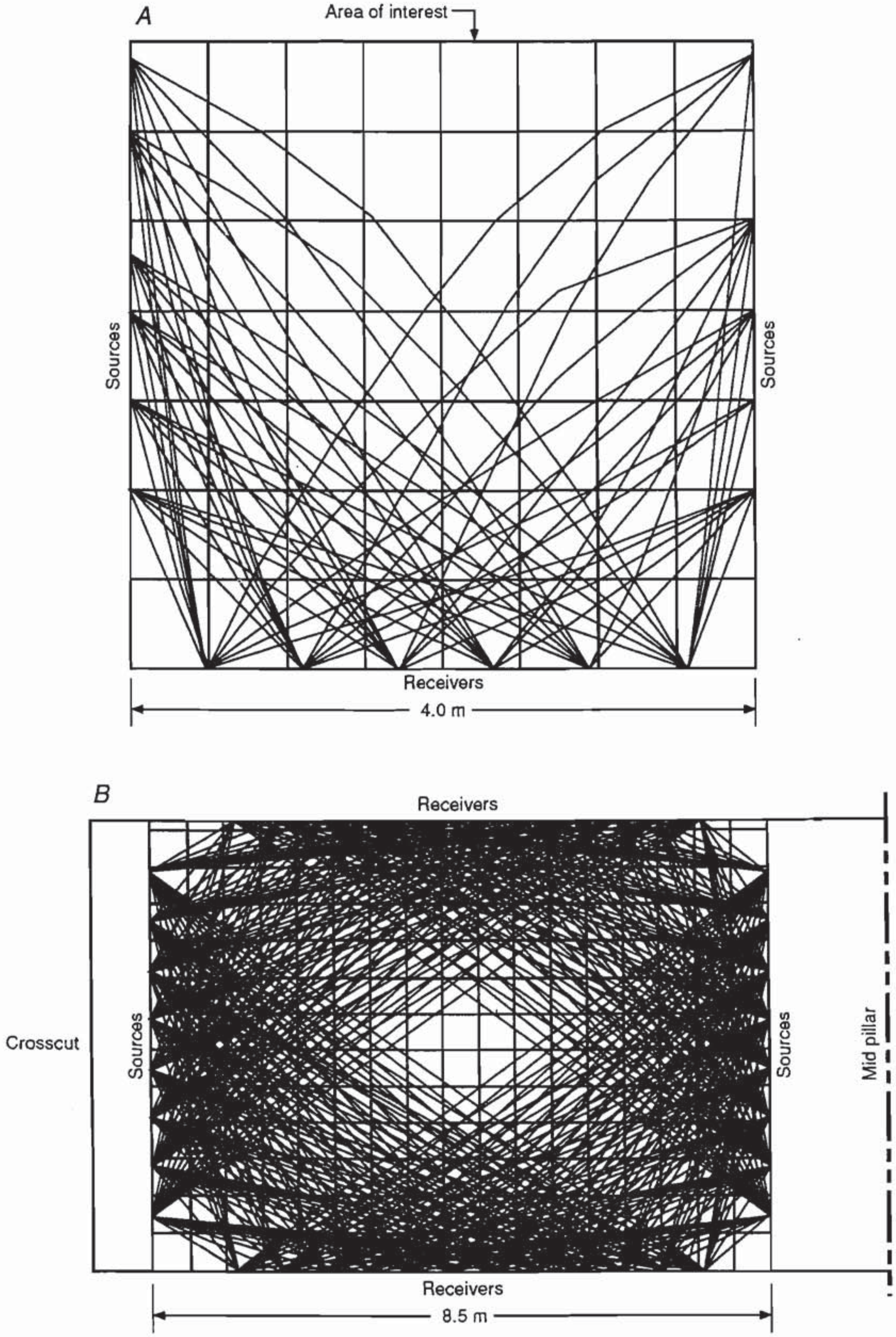
Figure 1
Considerations in Tomographic Surveys.





***A*, Types of typical geologic variations; *B*, location of sources and receivers.**

Figure 2
Ray Coverage as Influenced by Position of Instruments and Ray Bending.



***A*, Three-sided roof survey; *B*, four-sided pillar survey.**

Figure 3
Instrument Position and Mining Geometry.

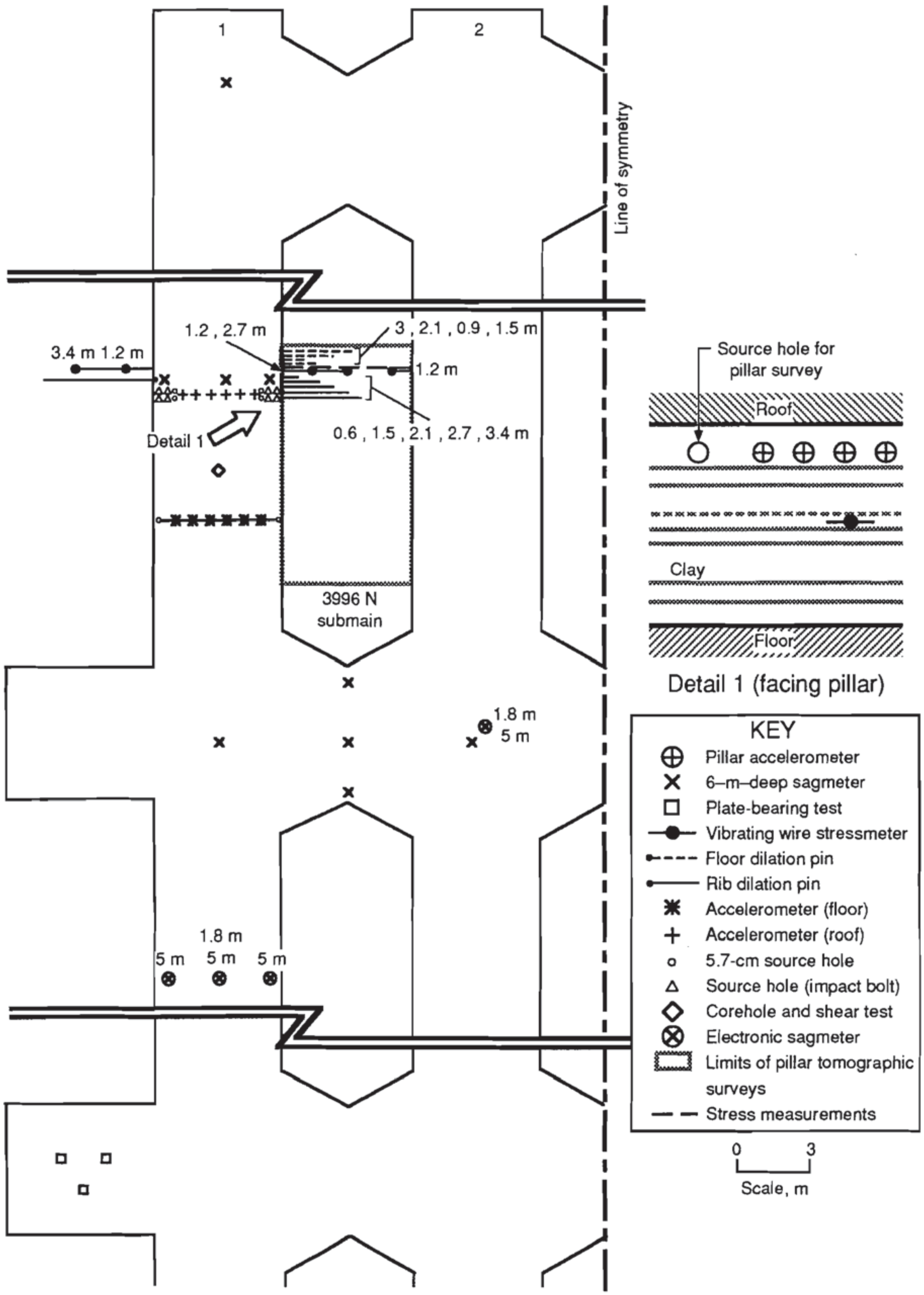


Figure 4
Details of Instrument Location.

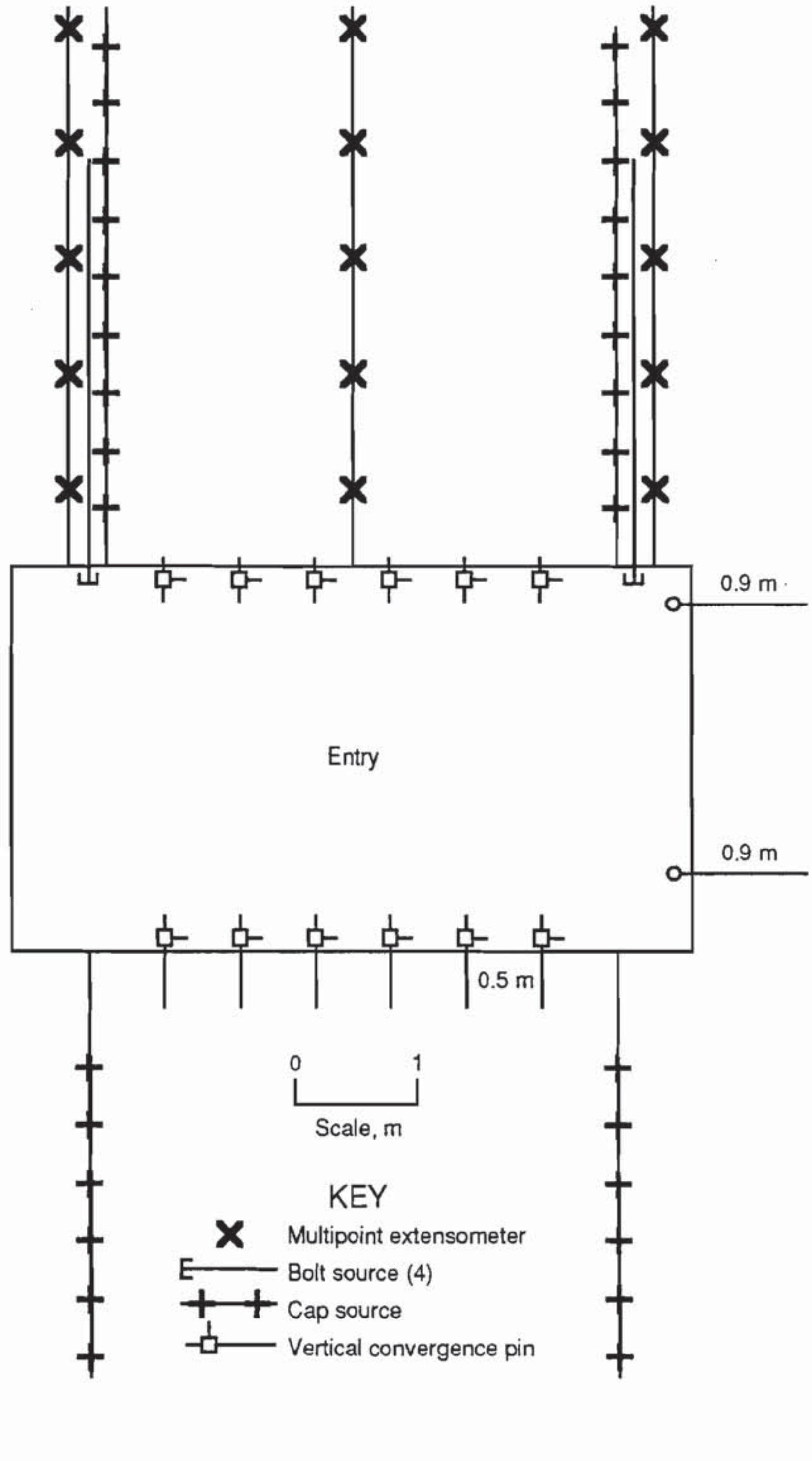
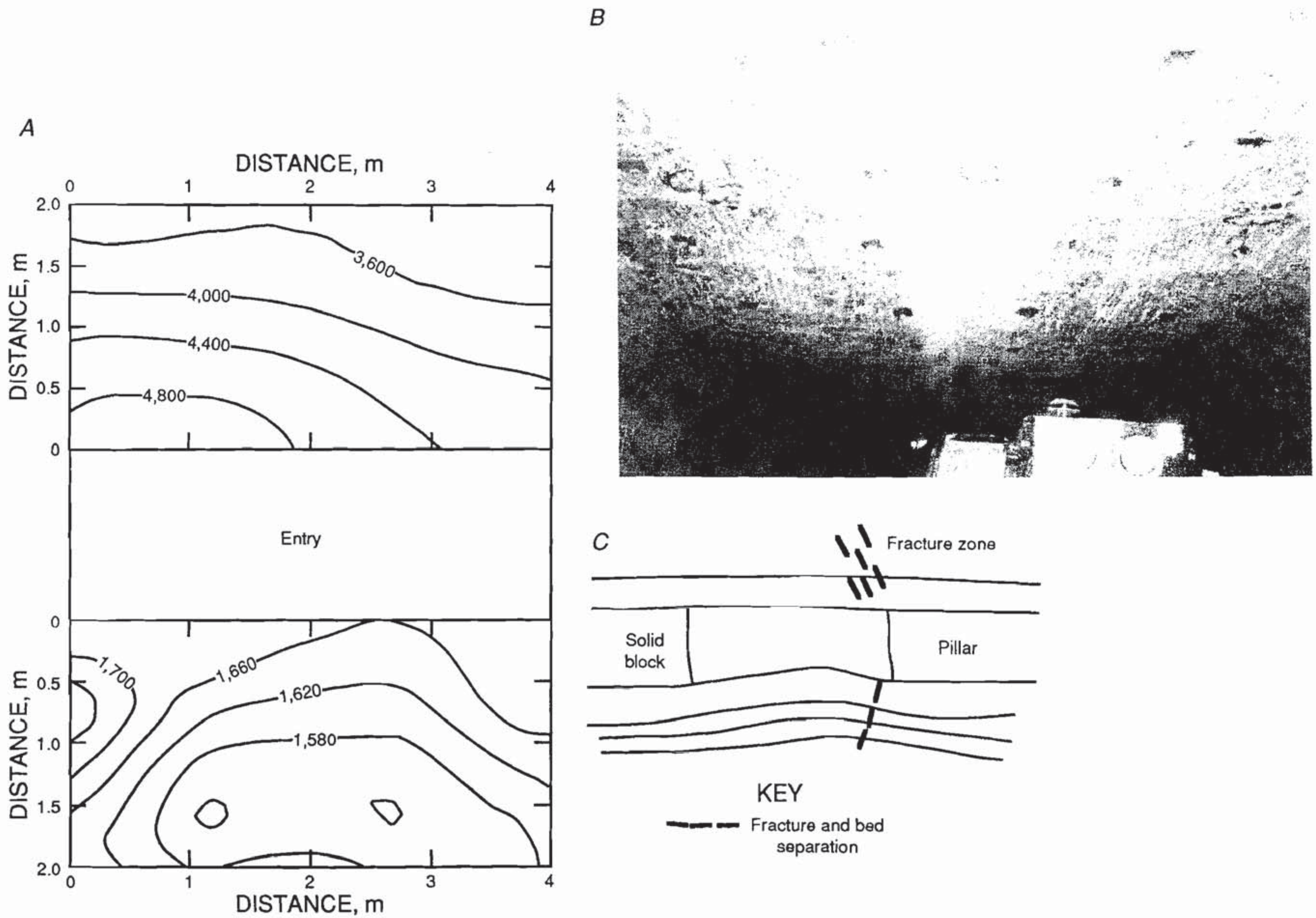
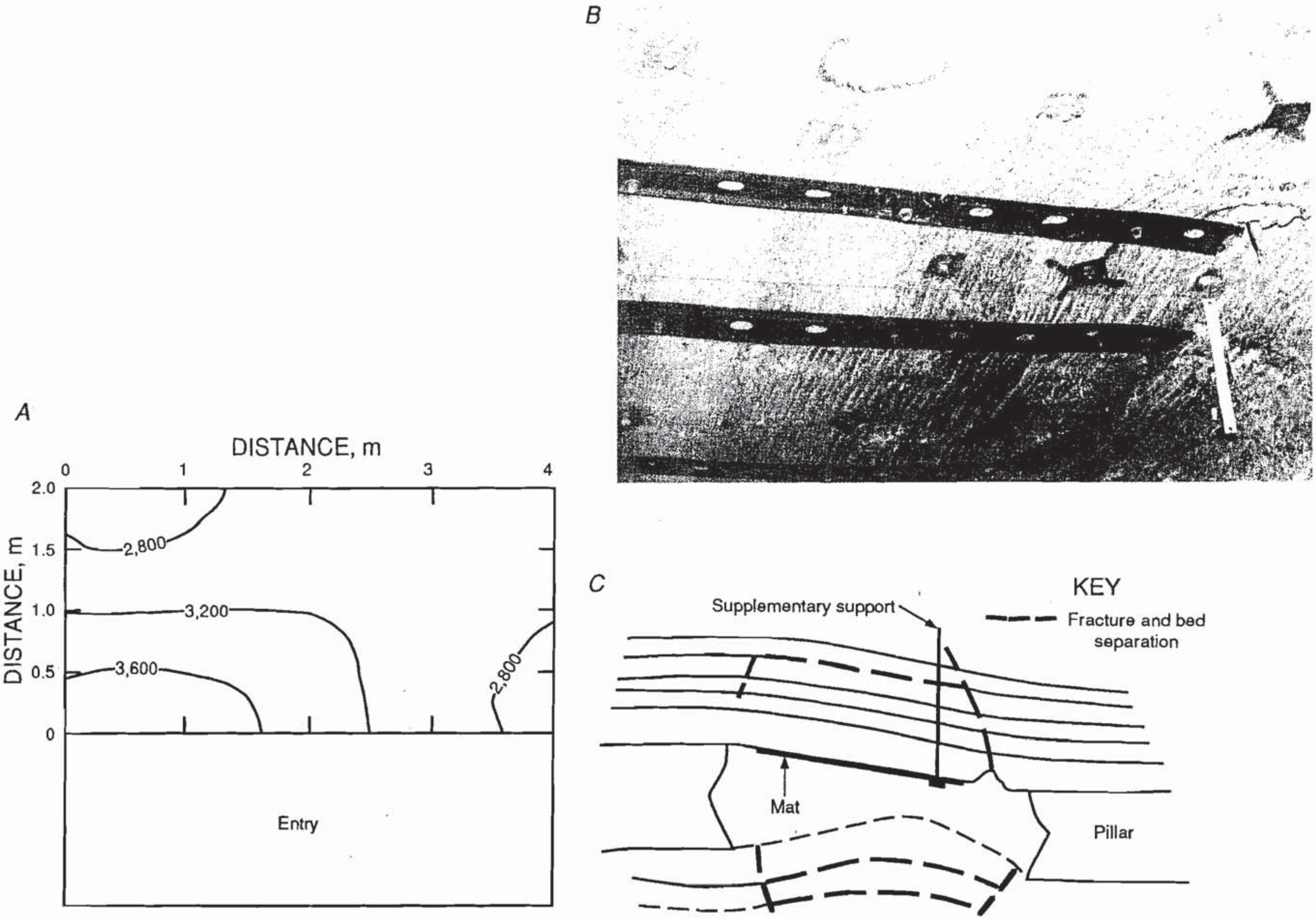


Figure 5
Velocity Contours and Ground Conditions at Development Face Position.



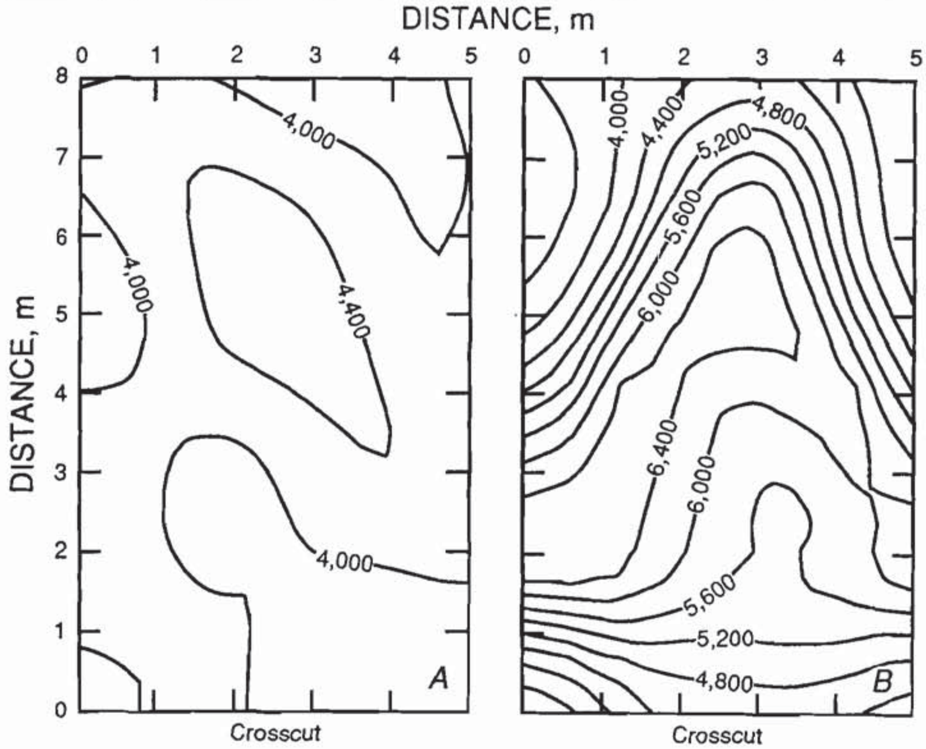
***A*, Velocity image, m/s; *B*, actual roof conditions; *C*, schematic of strata movements.**

Figure 6
Velocity Pattern and Ground Conditions at Retreating Face Position.



***A*, Velocity image, m/s; *B*, actual roof conditions; *C*, schematic of strata fracturing.**

Figure 7
Velocity Pattern in Mine Pillar, Meters Per Second.



***A*, Prior to retreat; *B*, at retreating face position.**

CONCLUSIONS

The application of tomographic methods to the study of time-dependent strata fracturing and stress changes was demonstrated using field measurements of the roof, floor, and pillar in a Western U.S. mine. The measurements were successful in identifying the location and timing of mining-induced fractures in the mine roof and floor. Pillar measurements revealed changes in velocity as the retreating face approached the instrumented pillar. This confirms laboratory investigations and a relationship between velocity and stress levels (Wepper and Christensen, 1991).

REFERENCES

Brooks, R. A., and G. DiChiro. Principles of Computer-Assisted Tomography in Radiographic and Radioisotopic Imaging. Phys. Med. Biol. 21, 1976, pp. 689-732.

Jessop, J. A., M. J. Friedel, D. R. Tweeton, and M. J. Jackson. Fracture Detection with Seismic Crosshole Tomography for Solution Control in a Stope. Paper in Application of Geophysics to Engineering and Environmental Problems, 5th Symposium (SAGEEP), ed. by R. S. Bell. Soc. Eng. & Miner. Explor. Geophy., 1992, pp. 487-508.

Maleki, H. An Analysis of Violent Failure in U.S. Coal Mines. Paper in Proceedings: Mechanics and Mitigation of Violent Failure in Coal and Hard Rock Mines. USBM Spec. Publ. 01-95, 1995, pp. 5-25.

Maleki, H. Effective Monitoring Techniques for Assessing Structural Stability. Paper in New Technology for Longwall Ground Control: Proceedings, U.S. Bureau of Mines Longwall Technology Transfer Seminar, compiled by C. Mark, R. J. Tuchman, R. C. Repsher, and C. L. Simon. USBM Spec. Publ. 01-94, 1994, pp. 117-129.

Maleki, H. Ground Response to Longwall Mining. CO Sch. Mines Q, v. 83, No. 3, 1988, 14 pp.

Maleki, H., W. Ibrahim, Y. Jung, and P. A. Edminster. Development of an Integrated Monitoring System for Evaluating Roof Stability. Paper in Proceedings, Fourth Conference on Ground Control for Midwestern U.S. Coal Mines, ed. by Y. P. Chugh and G. A. Beasley (Mt. Vernon, IL, Nov. 2-4, 1992). Dep. Min. Eng., S. IL Univ., 1992, pp. 255-271.

Maleki, H., Y. Jung, and K. Hollberg. Case Study of Monitoring Changes in Roof Stability. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., v. 30, No. 7, 1993, pp. 1395-1401.

Wepper, W. W., and N. I. Christensen. A Seismic Velocity-Confining Pressure Relation, with Applications. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., v. 28, No. 5, 1991, pp. 451-462.

Westman, E. C. Characterization of Structural Integrity and Stress State via Seismic Methods: A Case Study. Paper in Proceedings of 12th International Conference on Ground Control in Mining, ed. by S. S. Peng (Morgantown, WV, Aug. 3-5, 1993). Dep. Min. Eng., WV Univ. 1993, pp. 327-329.

Special Publication 01-95

Proceedings: Mechanics and Mitigation of Violent Failure in Coal and Hard-Rock Mines

Edited by Hamid Maleki, Priscilla F. Wopat, Richard C. Repsher,
and Robert J. Tuchman

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES
Rhea L. Graham, Director

Library of Congress Cataloging in Publication Data:

Maleki, Hamid N.

Proceedings : mechanics and mitigation of violet failure in coal and hard-rock mines / edited by Hamid Maleki ... [et al.].

p. cm. — (USBM special publication; 01-95)

Includes bibliographical references.

Supt. of Docs. no.:I 29.151 : 01-95.

1. Rock bursts—Congresses. 2. Mine roof control—Congresses. 3. Coal mines and mining—Safety measures—Congresses. 4. Mines and mineral resources—Safety measures—Congresses. I. Title. II. Series: Special publication (United States. Bureau of Mines); SP 01-95.

TN317.M35 1995 622'.28—dc20 95-7138 CIP