USE OF TOMOGRAPHIC IMAGING AS A TOOL TO IDENTIFY AREAS OF HIGH STRESS IN REMNANT ORE PILLARS IN DEEP UNDERGROUND MINES

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ABSTRACT

Rock masses in deep mines are subject to high stress, which can result in unexpected, violent failure of rock into mined-out openings. One method to evaluate relative stress is tomographic imaging, a technique based on the principle that highly stressed rock will demonstrate relatively higher velocities than rock under less stress (load). The success of tomography depends on subsequent surveys in which increases, decreases, or changes in locations and magnitude of stress are compared.

Researchers at two U.S. Bureau of Mines centers, the Spokane Research Center and the Twin Cities Research Center, have been investigating tomographic imaging as a tool for identifying stress in remnant ore pillars in deep mines. Work has proceeded at two mines, the Lucky Friday Mine, Mullan, ID, and the Homestake Mine, Lead, SD, and two successive tomographic surveys have been completed at each mine.

Software has been developed to produce three-dimensional tomograms showing areas of high and low velocities (stress) in pillars at both mines. Mined-out openings, haulageways, ramps, and crosscuts are areas of low velocity that correlate well to fractured rock and indicate low stress. Areas of higher velocity (therefore higher stress) are well delineated above backfilled stopes.

INTRODUCTION

Stress in deep underground mine pillars is difficult to detect and quantify. If undetected, the result can be unexpected and catastrophic failure of large volumes of rock into mined-out openings. Current methods of stress determination are expensive, time consuming, and confined to determinations at a single point.

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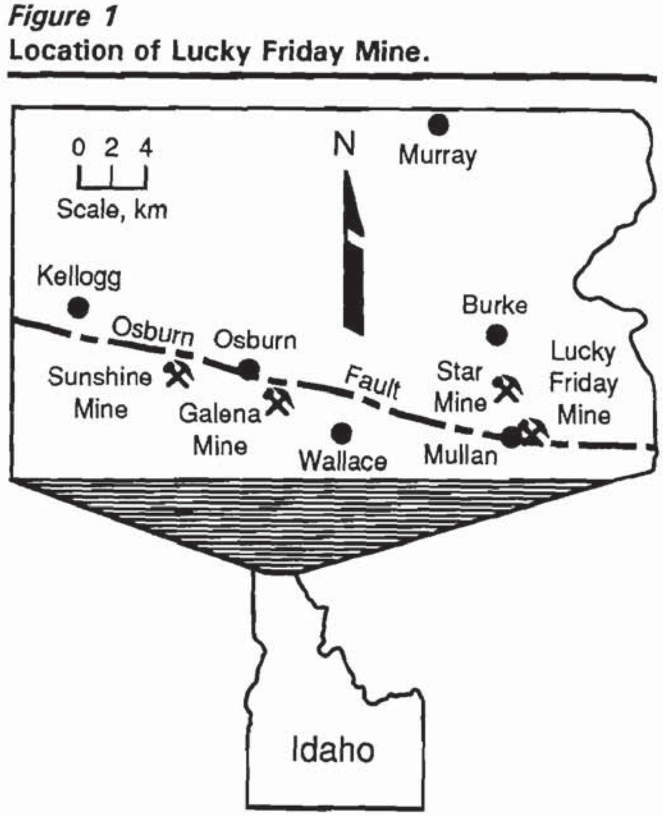
Using an impact source to send seismic waves through a rock mass and recording the velocities of these waves at receivers positioned around the area of interest enables the construction of a tomogram. A tomogram is a snapshot of the velocities and can be used along with information about the geology and seismicity of a pillar to assign relative stress to the pillar.

To evaluate the usefulness of the technique, U.S. Bureau of Mines (USBM) researchers conducted tomographic surveys in pillars at two deep underground mines, the Lucky Friday Mine, Mullan, ID (March and November

1993) and the Homestake Mine, Lead SD (July and October 1993). This paper describes work during the first survey in the Lucky Friday Mine. The objectives of the research were to enhance existing three-dimensional software to simulate stress based on observed velocities; utilize existing mine conditions for a tomographic survey without requiring additional mine development; determine if velocities could be used to identify areas of high and low stress in a rock mass; and use geologic information, seismic activity, and tomography as tools to determine the state of stress of a deep underground pillar.

The Lucky Friday Mine (figure 1) is accessed primarily by the Silver shaft, which extends to a depth of about 1,859 m below the surface. Levels are about 61 m apart; current mining is mechanized underhand cut-and-fill along a nearly vertical vein. Stopes average about 122 m long, 3 m wide, and 61 m high, with sublevels about 30 m apart. Load-haul-dump units are used for ore and waste removal. The pillar, which is approximately 152 m long, 91 m thick, and 61 m high, was mined by overhand cut-and-fill methods from the 5100 level upward about 21 m. This pillar was chosen for the survey because it is in an area known to have elevated stress levels; part of the pillar had already been mined and backfilled; access above, below, and around the pillar was sufficient for a survey; and seismicity was associated with the pillar.

Figure 1
Location of Lucky Friday Mine.



GEOLOGIC SETTING

The Lucky Friday Mine is developed primarily along a single, tabular, nearly vertical vein (the Lucky Friday). The vein occurs mainly in the Revett Formation, which is composed of Precambrian quartzite, sericite, and argillite. The vein ranges from several centimeters to about 4.3 m thick and contains massive galena, sphalerite, and tetrahedrite, which are the ore minerals for lead, zinc, and silver, respectively. Gangue materials are quartz and siderite. The vein is sigmoidal in shape and is bounded on the north by the North Control Fault and on the south by the South Control Fault. The vein generally coincides with a large anticline and dips 70° to 90° to the south, with a southeast rake. Because the vein dips more steeply than the anticline, it contacts increasingly older rocks with depth and intersects the Upper Revett about 549 m below the surface.

The pillar investigated at the Lucky Friday Mine is composed of mainly fine-grained vitreous quartzite, which occurs in flat, laminated-to-cross-bedded, 46- to 91-cm-thick beds that contain abundant quartz veins. Sericitic quartzite, next in abundance, is softer than vitreous quartzite and occurs in flat, laminated, 30- to 91-cm-thick beds. It appears randomly along bedding planes in the vitreous quartzite and is commonly associated with thin beds of argillite. Argillite is pale green to light brown. The argillite becomes clay-like when wet, similar to fault gouge. The argillite occurs in flat, laminated beds ranging from about 0.4 to 7.6 cm thick and is interbedded with both the vitreous and sericitic quartzites. Bedding can be defined by the argillite.

TOMOGRAPHIC METHODS

PRINCIPLES

Inducing a seismic wave through a rock mass and recording the velocities of the first arrivals of the wave at various geophones provides a base for tomographic imaging of a rock mass (figure 2). The velocities are statistically tested for validity, and average velocity is calculated on the basis of the principle that the more compact the rock mass (that is, the more loading or stress a rock mass contains), the higher the velocities. Low velocities would be associated with fractured rock masses or rock under less stress.

EQUIPMENT

The geophones used were 100 and 60 Hz (figure 3). The cables were 137 m in length, with 20 takeouts spaced 6 m apart. A Bison Digital Instantaneous Floating Point Signal Stacking Seismograph, Model 9024, Series 9000 (figure 4), was used for data collection. The seismograph was powered with a heavy-duty 12-V marine battery. A two-pair shielded cable was also used to communicate to the seismograph operator and send sledgehammer trigger signals to the seismograph. A distinct advantage of the field equipment was its compactness, which enabled it to be easily set up on a flatcar (figure 5).

SOFTWARE AND HARDWARE

Underground, data from the seismograph was downloaded to a 486 computer (figure 6). The first-arrival waves to reach the geophones were picked and stored. All geophone coordinate data were input into a spreadsheet along with the first-arrival times. MIGRATOM,[4] a USBM-developed software package, was used to process data from the spreadsheets, and two- and three-dimensional tomograms were generated. Final contouring of the tomograms was done with a commercial software contouring package.

DATA COLLECTION

Access to nearly all sides of a pillar is critical to ensuring that ray paths cross all parts of a pillar. The first step was to establish suitable geophone locations. Most mines use mechanical rock bolts with metal plates. Because the geophones used were mounted with bolts, it was decided to mount the geophones on the end of a rock bolt or the metal plate. At about 6-m intervals, the ends of the rock bolts were drilled and tapped (figure 7). If the bolt could not be drilled, the rock bolt plate was drilled and tapped instead. Figure 8 shows geophone locations on the 4900 and 5100 levels. Using the mine coordinate system, project personnel surveyed each bolt from the existing spads in the roof of the drifts, crosscuts, or haulageways. Sixty-two geophones were installed on the 4900 level and 66 were installed on the 5100 level. The source used for generating a signal to the seismograph was a 5.4 kg sledgehammer (figure 9). Twenty to thirty impacts per bolt were needed to stack signals on the seismograph.

A two-dimensional survey was completed for each level. To complete a three-dimensional survey, geophones were positioned on one level and the signals were generated on the other. One complete survey, using three workers, took four 8-h shifts. Because drilling, blasting, and noise from equipment during the day shifts interfered with signal recording, work was done during the 11:00 p.m. to 7:00 a.m. shift. This time worked well because the survey then resulted in a minimum amount of interference with other mining activities.

[4]Jackson, M. J., and D. R. Tweeton. MIGRATOM—Geophysical Tomography Using Wavefront Migration and Fuzzy Constraints. USBM RI 9497, 1994, 35 pp.

Figure 2
Location of Receivers Around Pillar in Lucky Friday Mine, 4900 Level.

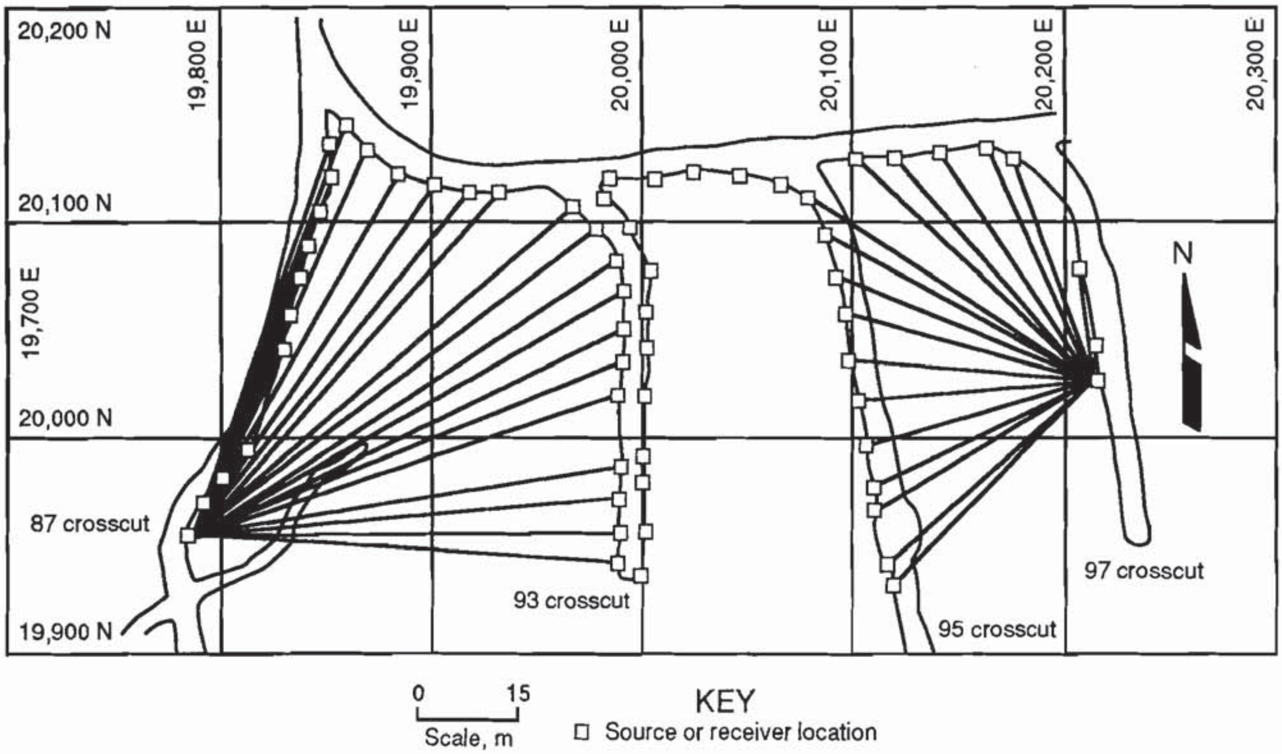


Figure 3
Geophones Attached to Cable Along Wall.

Figure 4
Seismograph.

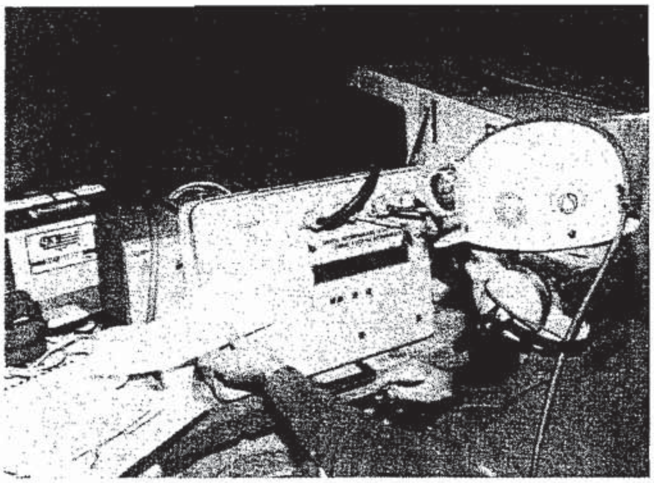


Figure 5
Data Collection Equipment on Flatcar.

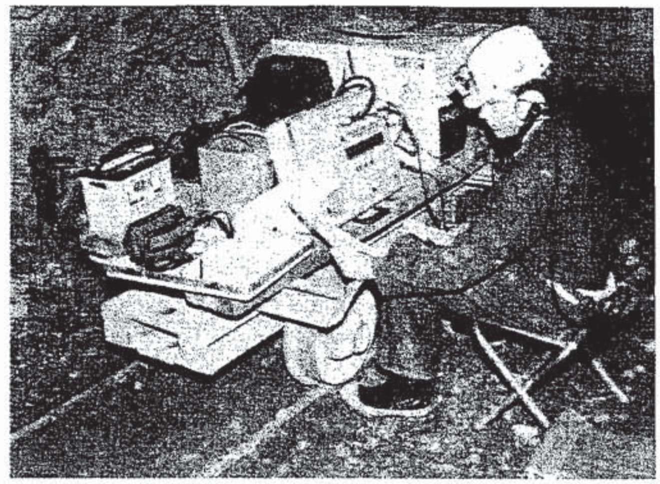


Figure 6
Downloading Data From Seismograph to 486 Computer.

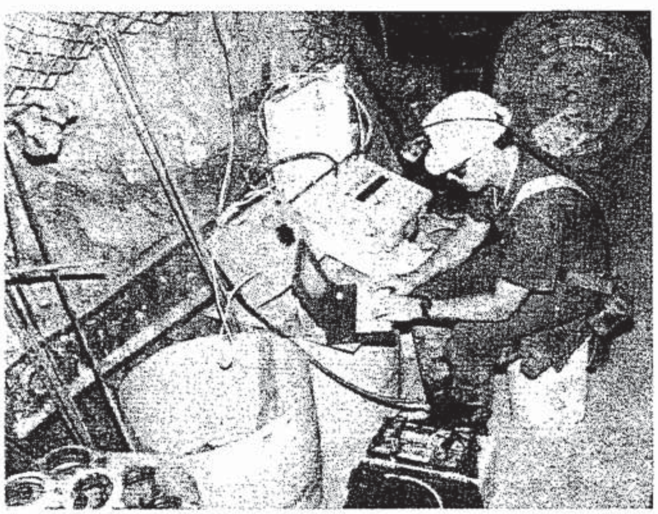


Figure 7
Drilling Rock Bolt Plate.

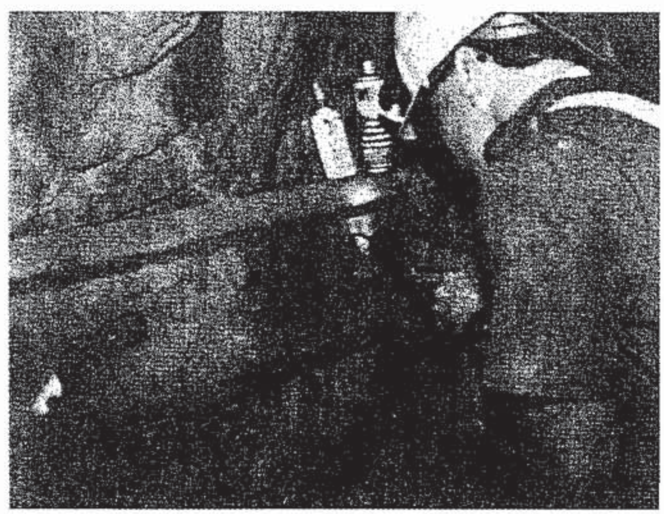
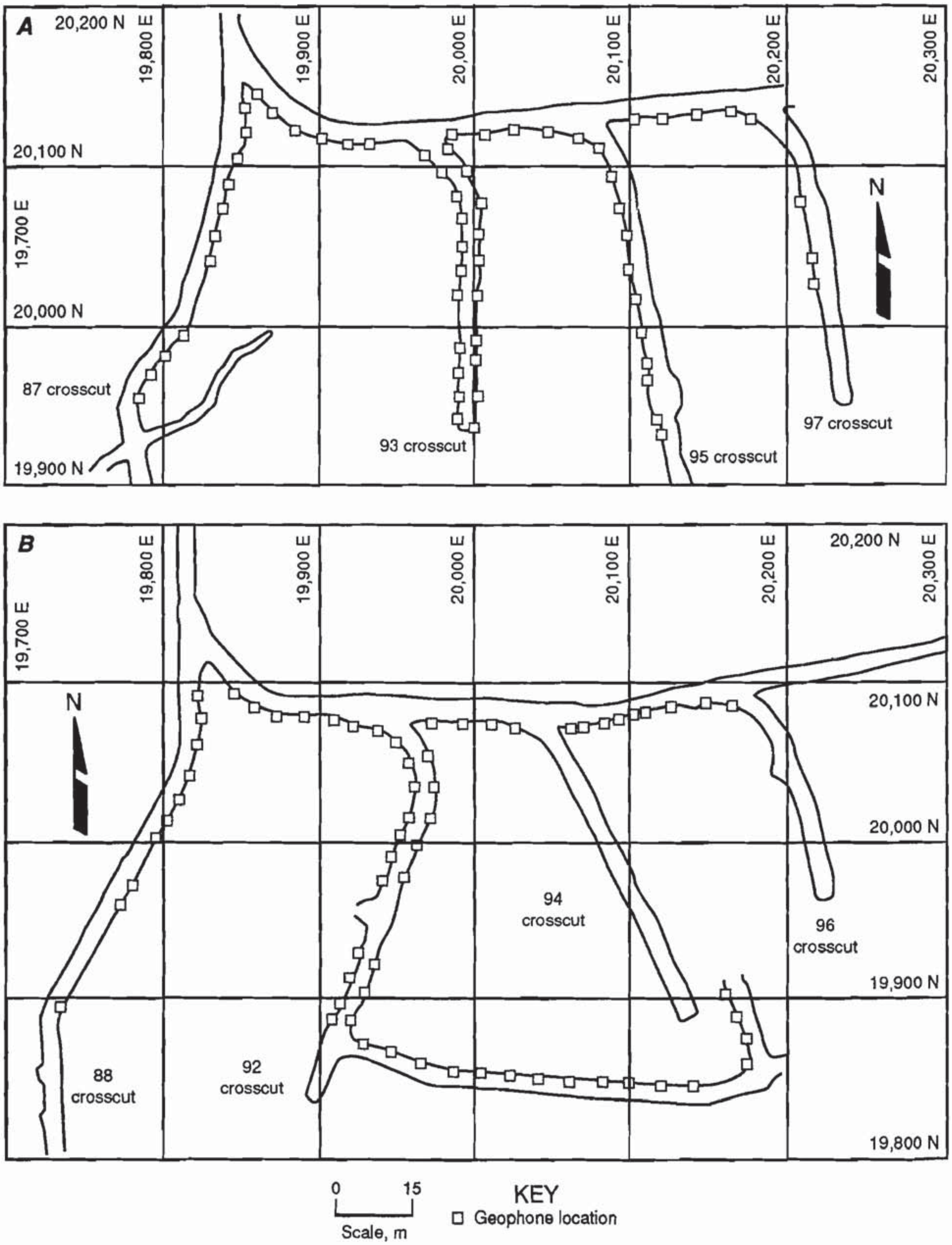


Figure 8
Location of Geophones.



A, **4900 level;** *B*, **5100 level.**

Figure 9
Using Sledgehammer To Create Seismic Energy.

INTERPRETATION OF TOMOGRAMS

Figures 10 and 11 are plan-view tomograms of the 4900 and 5100 levels, respectively, and figure 12 shows cross sections of the pillar looking east from the mine's east-west coordinate system at 20,000 and 20,050. Based on the tomograms, figures 10 and 11 clearly show regions of low velocity around mine openings and regions of high velocity near the center of the pillars created by the crosscuts (between crosscuts 87 and 93 and between 93 and 95) (figure 8*A*). This pattern reflects a reasonable stress scenario that a finite-element model would predict for mining the pillar. Areas of very high stress (figure 11) also appear in the pillar east of the 92 crosscut. Figure 12 shows several areas of high stress between levels. Most conspicuous are the areas of high stress above the mined-out vein. These areas of the pillar were abandoned several years ago because high stress in the area forced mining to halt. Directly below the upper backfilled vein on the 4900 level (figure 12*B*) is another large area of high stress. Based on the tomograms, there is a considerable portion of the pillar that is under high stress and that may require destressing prior to mining. Low velocities are mainly associated with development openings, which would coincide with a fractured skin along the openings.

The seismic data shown in figures 10, 11, and 12 were collected 90 days before, during, and 90 days after the survey. Figures 11 and 12*A* show increased seismicity in the area of the ramp from the 5100 level down. Physical inspection of the ramp verified that the ramp had indeed been hit by numerous seismic events, as evidenced by the shattered condition of the back and walls. Figure 12*B* also shows increased seismicity associated with high stress just above the 5100 level between the backfilled veins.

Figure 10
P-Wave Velocity, 4900 Level.

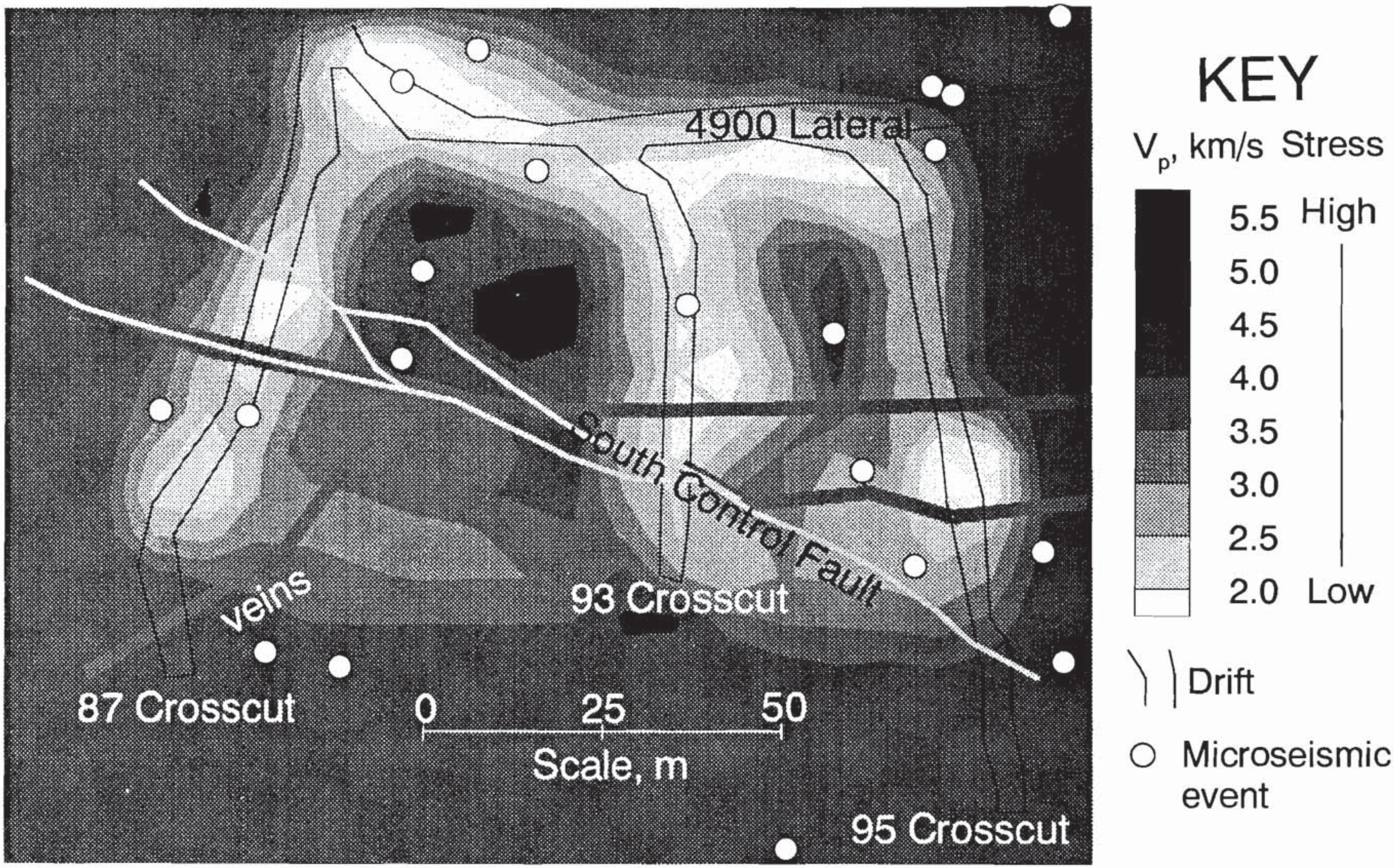


Figure 11
P-Wave Tomograms, 5100 Level, March 1993.

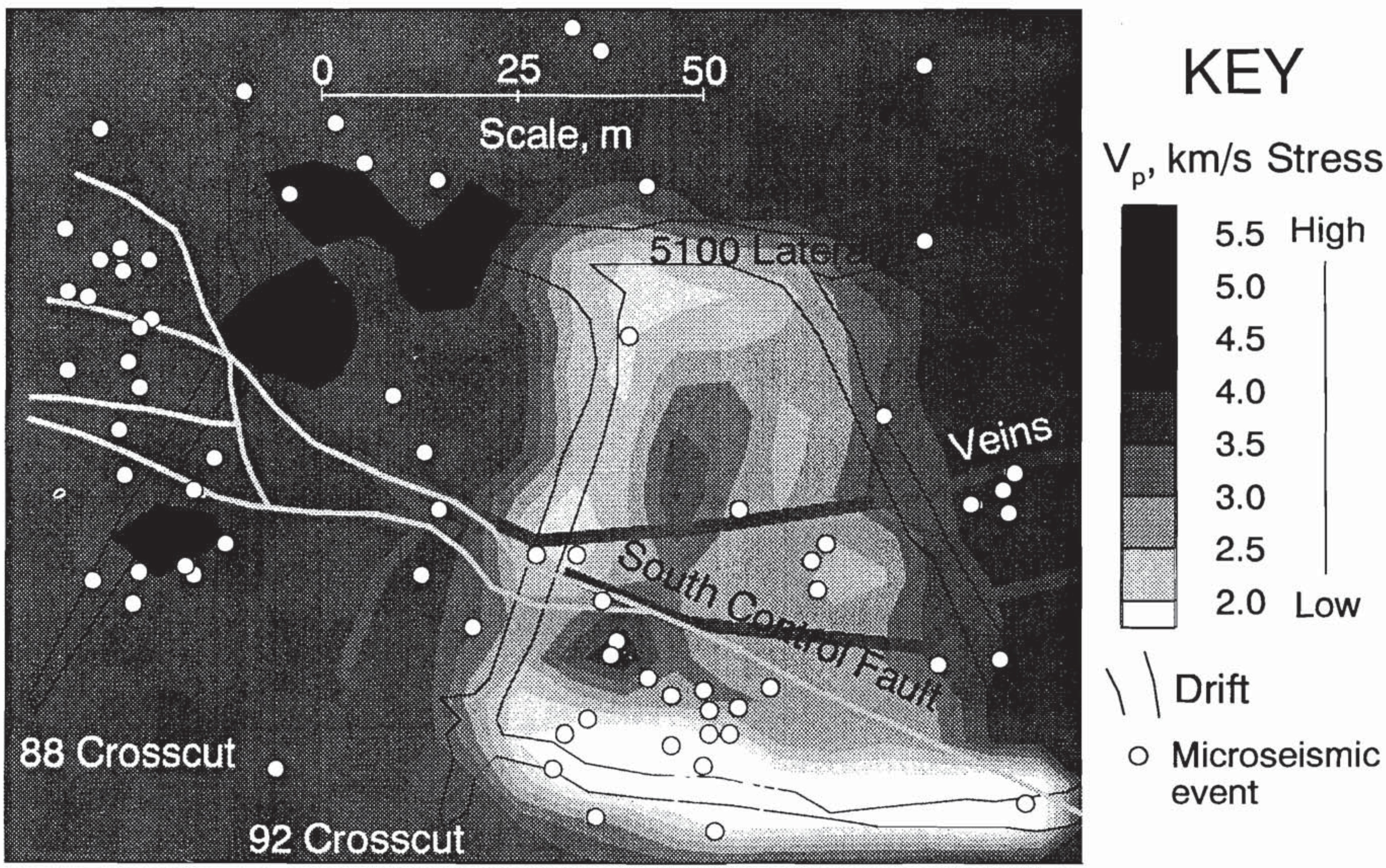
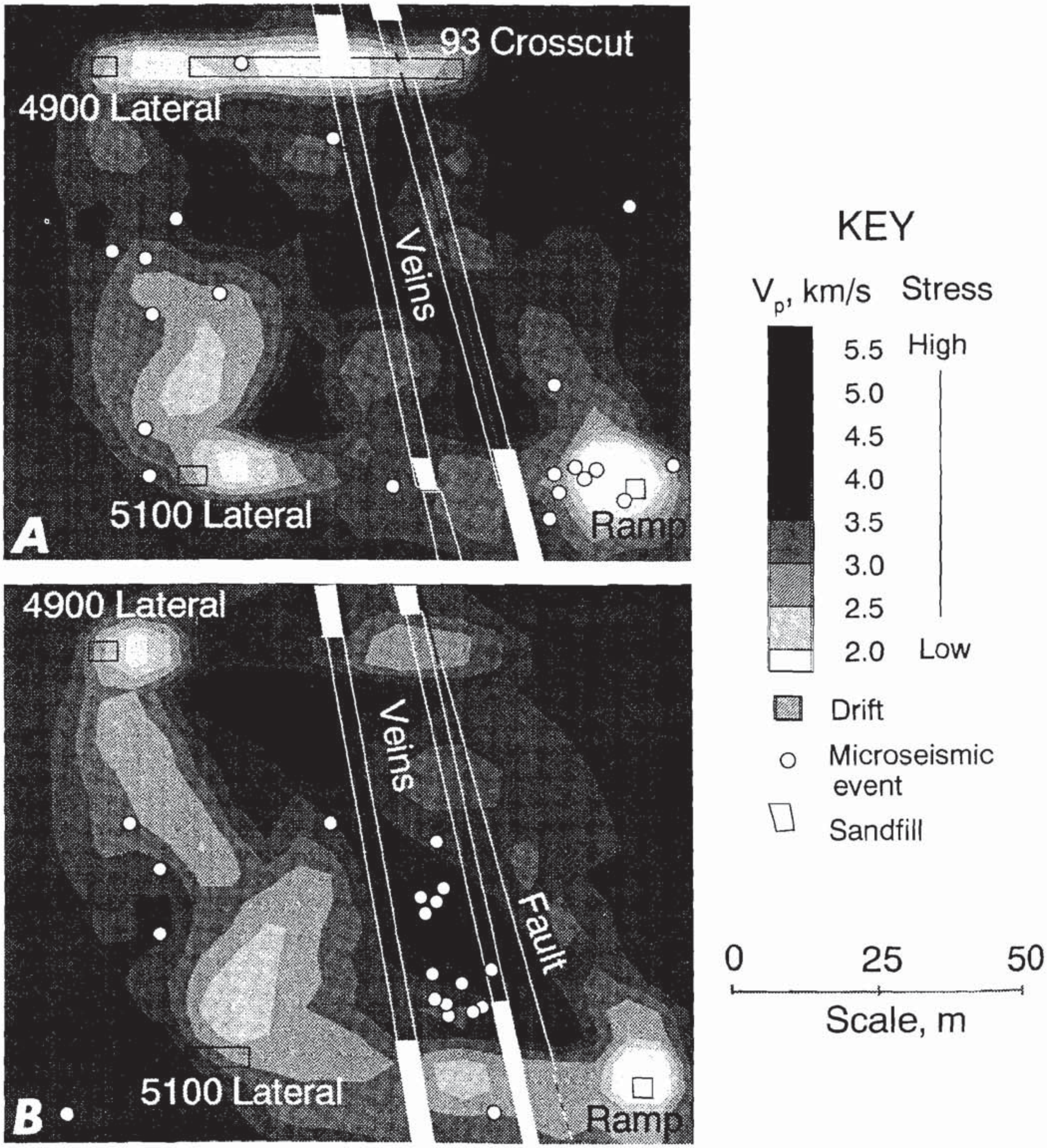


Figure 12
P-Wave Tomograms, March 1993.



View to the east. Mine coordinate system: *A*, 20,000 Easting; *B*, 20,050 Easting.

CONCLUSIONS

Three-dimensional tomograms were produced using updated versions of MIGRATOM. Existing mine support components (rock bolts, rock bolt plates, and spads) proved satisfactory for conducting the survey. Wave velocities from an impact source identified areas of high and low stress and correlated well with finite-element models of stress distribution.

Tomographic surveys to delineate areas of high and low stress in a deep underground pillar have proven to be useful. The advantages of tomographic surveys as compared to conventional methods of stress determination, such as overcoring, are that the cost of a tomographic survey is considerably less than costs of overcoring; the time needed to conduct a tomographic survey is less; repeating a tomographic survey is very easy; and stress analyses can be done for an entire pillar rather than just one point.

Tomographic surveys can be conducted by engineers, mine planners, and geologists to analyze stress conditions before and after blasting, identify damaged areas or bad ground associated with areas of low stress in fractured ground, and plan mine development on the basis of stress conditions. Mining companies will benefit by having a snapshot of pillar stress conditions prior to development. Knowing the location of areas of high and low stress in a pillar will result in increased safety for miners.

Future work will involve another deep underground mine in which stress in a pillar resulted in a burst that killed a miner.

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