EFFECTIVE MONITORING TECHNIQUES FOR ASSESSING STRUCTURAL STABILITY

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ABSTRACT

Roof, pillar, and floor instability have long influenced mine safety, ventilation, productivity, and resource recovery. Based on decades of measurements in ten U.S. mines, suitable measurement techniques and preliminary stability evaluation criteria are proposed for prudent structural stability assessments. Three methods that use the changes in rock deformation, fracturing, and stress conditions are shown to be useful and effective for routine stability evaluations and show potential for improving safety in underground excavations.

INTRODUCTION

During the life of underground mines, more than 100 km of entries are excavated to access and extract the ore. Since both geologic and stress conditions may vary across a mine (Maleki and others, 1994), there is a good possibility that every mine experiences stability problems sometime during its life. From a practical point of view, stability problems are those influencing the capability of an entry to provide safe access, efficient ventilation, and sufficient space for material transport. Thus, mine roof falls, significant rib dilation (as a result of pillar failure), and significant floor heave are considered to be stability problems in the context of this paper.

Historically, the mining industry has depended on quick observations of strata deformation and failure (Maleki, 1988a), bolt failure, and lithologic changes (Hilbert, 1978) to evaluate stability. These preliminary evaluations sometimes have been used to make significant changes in mine layout and support systems, which may affect the economics of a mine. Because of the subjectivity involved in these visual observations, the mining process is slowed, creating inefficiencies and safety concerns during the time a decision is being reached.

The U.S. Bureau of Mines (USBM) has made significant contributions to the development of innovative measurement techniques for prudent stability assessment. Unlike observational techniques, these measurements are quantitative and enhance both an understanding of the failure process and the decisionmaking process.

Following a review of common coal mine stability problems and monitoring techniques, case studies are presented to demonstrate the application of these techniques to detect imminent stability problems. New developments in the application of geophysical techniques are emphasized, for such techniques show great potential for quantifying abnormal fracturing and stresses that lead to ground failure.

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REVIEW OF STABILITY PROBLEMS

Stability problems in sedimentary mines are influenced by variations in lithology, structure, hydrology, and stress conditions (table 1). Roof and floor instabilities are influenced by both strength and stress regime. Unconsolidated carbonaceous shales and underclays are known to detach from other strata, contributing to mine roof falls and floor heave. Similarly, discontinuities adversely influence rock mass strength.

Table 1.—Factors affecting stability in coal-measure rocks

Factor	*Example*
Lithologic:	
Unconsolidated, uncohesive rock.	Carbonaceous shale, underclay.
Laminated, low-friction planes	Thin-bedded strata.
Nonuniform lithology	Channels, riders.
Structural:	
Unfavorable discontinuities ..	Joints, faults, dikes, cleats, slickensided joints.
Hydrologic and gaseous:	
Hydrostatic and/or gas pressures.	Channels, bumps.
Chemical decomposition	Underclays.
Stress-related:	
Roof failure	Cutters, kinks, delamination.
Pillar failure	Squeezes, bumps.
Floor failure	Buckling, squeezing.

Both groundwater and gas trapped within rock strata assert significant pressure within mine structures. The margins of sandstone channels, for example, can be influenced by both saturated groundwater head and depositional effects that can reduce rock mass strength because of differential compaction.

Excessive far-field horizontal stresses can enhance deformation along laminated rock interfaces and may form cutters and kinks in brittle material (Maleki and others, 1994) depending on strength and stiffness of mine strata. High stresses can also contribute to buckling of floor strata (Aggson, 1978) and squeeze of underclays.

Changes in vertical stresses as a result of topographic changes and/or secondary mining may cause coal pillar stability problems. Pillar failure mechanisms in U.S. coal mines are described by Maleki (1992a) and consist of gradual rib dilation, pillar failure in a panel (squeeze), and violent failure in the form of coal bumps. Coal bumps are influenced by the stiffness of the mine loading system (Wawersik and Fairhurst, 1970).

From this review, it is evident that stability problems are complex and influenced by strength, stiffness, and stress. There are, however, changes in rock conditions that occur during the failure process that can be used to evaluate stability. Because failure is physically associated with deformation, dilation, microcracking, fracturing, and destressing, measurement techniques that monitor changes in these properties can be effective tools for assessing structural stability.

REVIEW OF MONITORING TECHNIQUES

To monitor stability, changes in two physical properties may be measured: (1) deformation and fracturing and (2) stress conditions. Stability assessment is generally accomplished by comparing measurements between initial (or expected) conditions and predetermined critical levels for the material under investigation. For example, if changes in seismic velocities reach a critical level of 17%, the mine roof is expected to behave inelastically and would benefit from supplementary support (Maleki, 1993b).

Measurements of deformation and fracturing have been used extensively to assess mine roof stability (Maleki, 1988a, 1993a) and yield pillar performance. These measurements are inexpensive, simple, and reliable. Deformation measurements are obtained with extensometers and roof-to-floor convergence meters and are supplemented by borescope observations of fracture development within boreholes. Development of failure zones in coal pillars is similarly associated with rib fracturing and dilation, which is measured with dilation points and tape extensometers (Maleki, 1988b).

Fracture initiation has been monitored using microseismic emissions (Repsher and Steblay, 1985), and fracture density has been studied recently using a controlled source and tomographic techniques (Maleki and others, 1993). The latter approach has allowed changes in roof stability to be compared with roof deformation and fracturing, which can significantly influence dynamic properties such as velocity, attenuation, Young's modulus, and Poisson's ratio. These measurements are available from recent studies at three sites and have great potential for widespread use in assessing stability problems and evaluating sites in detail.

Controlled source techniques have also been used to identify fracture zones and zones of high stress in pillars (Jung and others, 1991; Friedel and others, 1993; Westman, 1993). The latter is based on experimental evidence showing an increase in seismic velocity with stress increase.

Figure 1 illustrates typical geometries used in a controlled-source tomographic survey to evaluate mine roof and floor stability. Pillar surveys are similar except that there is usually access to all sides of a pillar, while contact is limited to three sides (two source boreholes and the roof) for roof or floor surveys. The impact source is generally some sort of hammer that transmits energy to the rock within source boreholes or directly to the pillar. Accelerometers are attached to the mine roof, floor, or pillar to receive the signal generated by the impact. These techniques quantify wave velocity within a volume of rock (see "area of interest" in figure 1) in contrast to obtaining point measurements when using sagmeters.

The principle of crosshole seismic tomography is shown in figure 2, where the structure under investigation is surveyed by a high density of waves traveling between sources and receivers. This is analogous to the use of a computerized axial tomography (CAT) scan of the human body, but sound waves are generated instead of x-rays. Nonlinear (curved) rays are used to accommodate ray bending, which occurs when changes in geologic conditions cause significant velocity differences.

Inverse iterative calculation methods are used to calculate a two-dimensional picture of velocity distribution in the mine structure bounded by the receivers and amplifiers. Since seismic velocity is influenced by fracturing and stresses, these seismic profiles can provide snapshots of variations in fractures, stress patterns, and stability of the structure under investigation (Maleki and others, 1993).

The components of a crosshole seismic survey developed for routine underground applications are shown in figure 3. A PC-based, 13-channel system with programmable gains capable of acquiring up to 150,000 samples per second was used for data acquisition. This system utilized an analog digital board, amplifiers, filters, and a trigger unit (Maleki and others, 1992).

Stress measurements can also provide an assessment of structural stability, particularly when these measurements are compared with expected stress profiles based on numerical models. Overcoring techniques and borehole deformation gauges developed by the USBM are among the most direct and reliable methods of determining stress (Bickel, 1993; Maleki and others, 1994) and are routinely used for mine layout design.

The above methods are most suitable for monitoring changes in rock mass deformation and stress conditions. There are other useful measurements that indicate strata movement, but do not directly lend themselves to evaluations of structural stability. Measurements of bolt tension (Maleki, 1992b), for example, provide indirect indications of roof movements, but data analysis is complex because of the interaction of rock and support elements.

APPLICATION RESULTS

Typical results from long-term measurements in U.S. sedimentary mines are presented to examine the application of these measurements and existing criteria for structural stability evaluations. Three examples are presented using deformation, seismic velocity, and overcoring stress measurements for assessment of mine roof stability problems.

ROOF DEFORMATION HISTORY

Measurements of amount and rate of roof deformation have been extensively used in both longwall and room-and-pillar retreat mining systems (Maleki, 1993a, 1988a). Because there is a large database involving a variety of geologic and stress conditions, there are preliminary criteria for the routine use of this technique in underground coal mines.

Measurements in seven U.S. mines have indicated that most coal-measure rocks deform 2 to 7 cm prior to roof collapse, then accelerate to a critical velocity called the critical rate. Between the initiation of the critical rate and the actual mine roof fall, a period of time elapses that is called time-to-caving.

The rate of roof movement is a good indicator of roof stability, for it indicates a change in the stability of the whole mining system. A change from a steady rate of

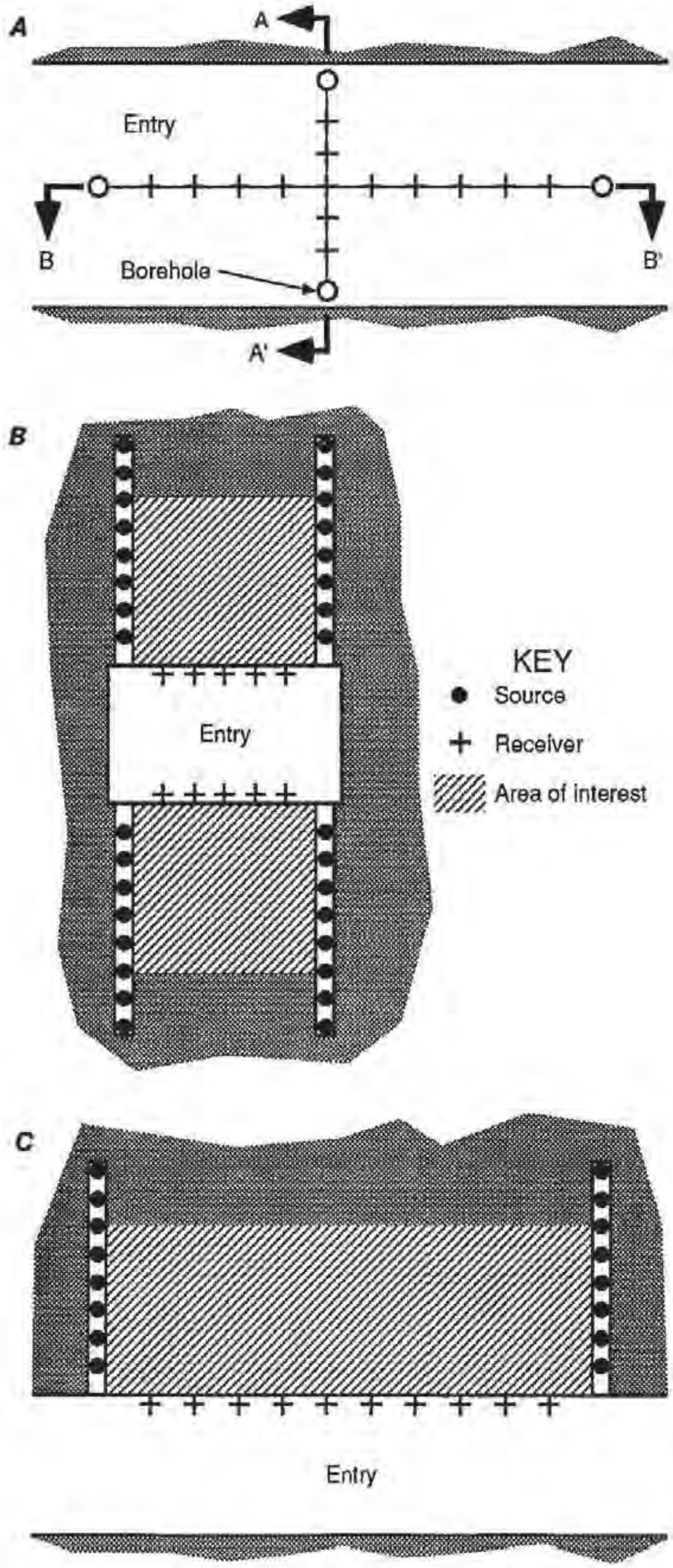

Figure 1.—Typical three-sided seismic surveys of mine roofs and floors. *A*, Plan view; *B*, cross section along A-A′; *C*, cross section along B-B′.

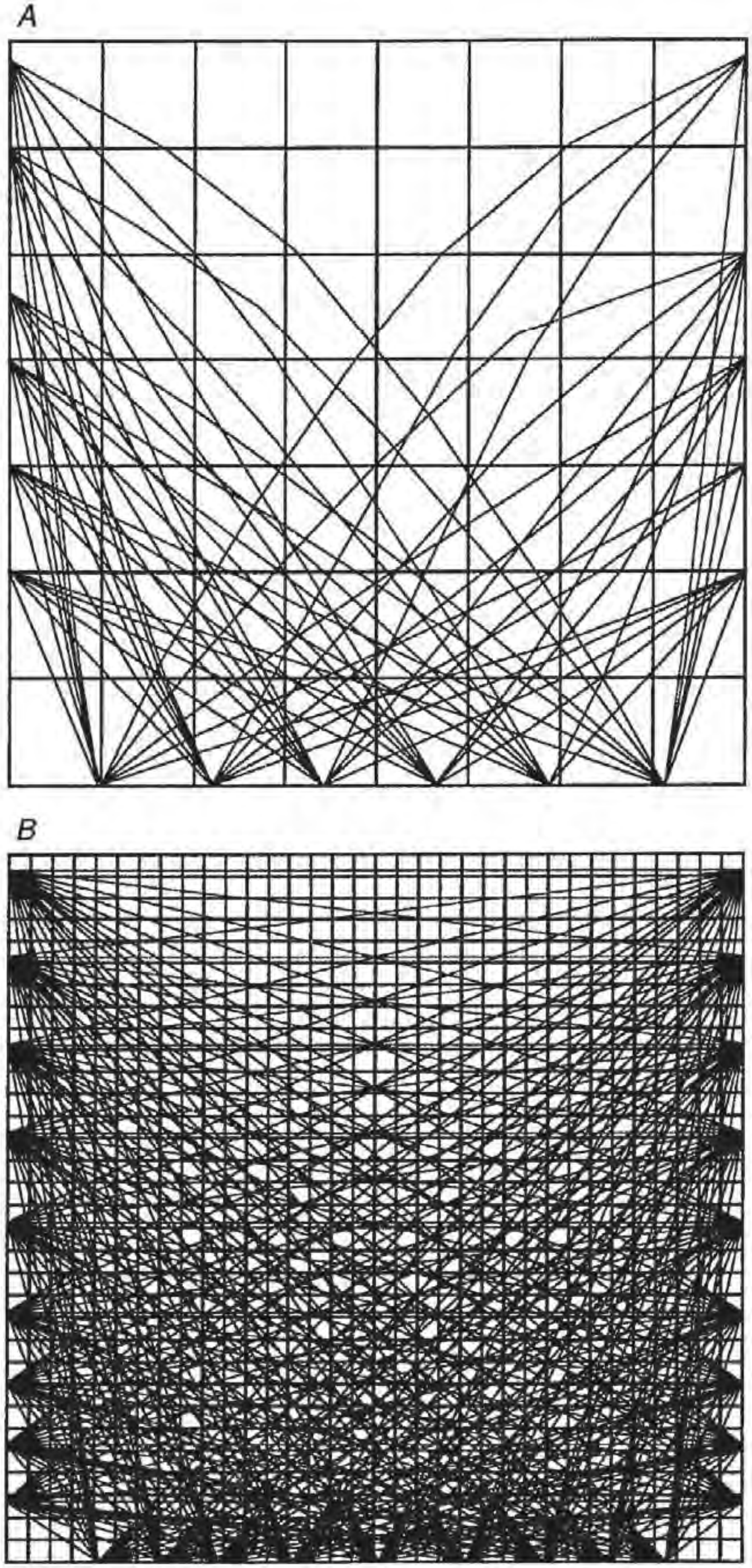

Figure 2.—Typical ray path for three-sided seismic survey in (*A*) mine roof or floor and (*B*) coal pillar.

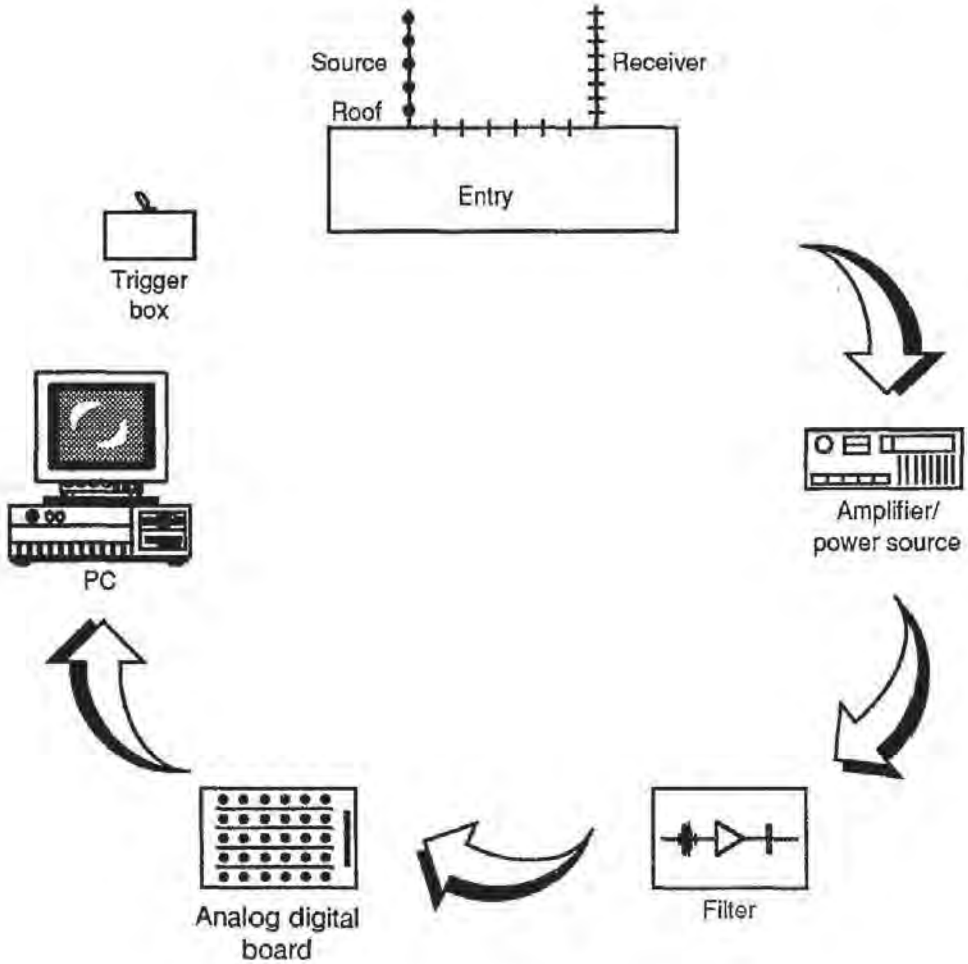

Figure 3.—Data acquisition system.

movement to a high (critical) rate can indicate roof block detachment, loss of support effectiveness, roof shearing by pillars, or impending coal pillar failure.

A history of relative roof deformation is presented in figure 4 for the middle entry of a longwall headgate. The span was 6 m; the immediate mine roof consisted of mudstone overlain by a sandstone channel, and the primary support was 1.2-m-long mechanical bolts and straps.

Roof deformation was monitored by two wire sagmeters, with anchors 1 (at 2.5 m) and 2 (at 1 m) positioned above and below the bolt anchor horizon, respectively. Relative roof movements were calculated. The difference between the two curves in figure 4 reflects bed separation in the mine roof.

After development, roof movements reached 0.05 cm/d, resulting in roof flaking. Installation of posts reduced the rate of roof movement, but did not stop bed separation at the sandstone contact. As the longwall face approached within 100 m of the instrument, bed separation and rate of roof movement significantly increased. Installation of additional support slowed movement, but another accelerated roof movement and bed separation cycle occurred as the longwall face came within 30 m of the instrument. This was followed by a mine roof fall that occurred approximately 4 days after the last accelerated roof movement.

The critical rate of roof movement and the time-to-caving are best established by actually monitoring unstable mine roofs. A critical rate of roof sag of 0.05 cm/d was determined based on a total of 142 measurements in 3 mines with 6-m spans and stable pillars (table 2). This critical rate was based on roof sag measurements along the gate roads of five panels where no secondary support had been installed. Installation of secondary supports generally stabilized roof movements; therefore, measurements taken near secondary supports were excluded from the study. Maleki (1993a) has established these same caving parameters for another four pillar-pulling operations where spans are gradually increased to 15 m and pillars crush to residual strength.

Table 2.—Critical rate of roof sag for three mines using 6-m spans

Mine	Critical rate, cm/d	Time-to-caving, days	Number of measurements
1	0.06	2- 8	115
2	[1]0.08	NAp	24
3	0.05	9-11	3

NAp Not applicable.
[1]No failure was recorded, but area was stable.

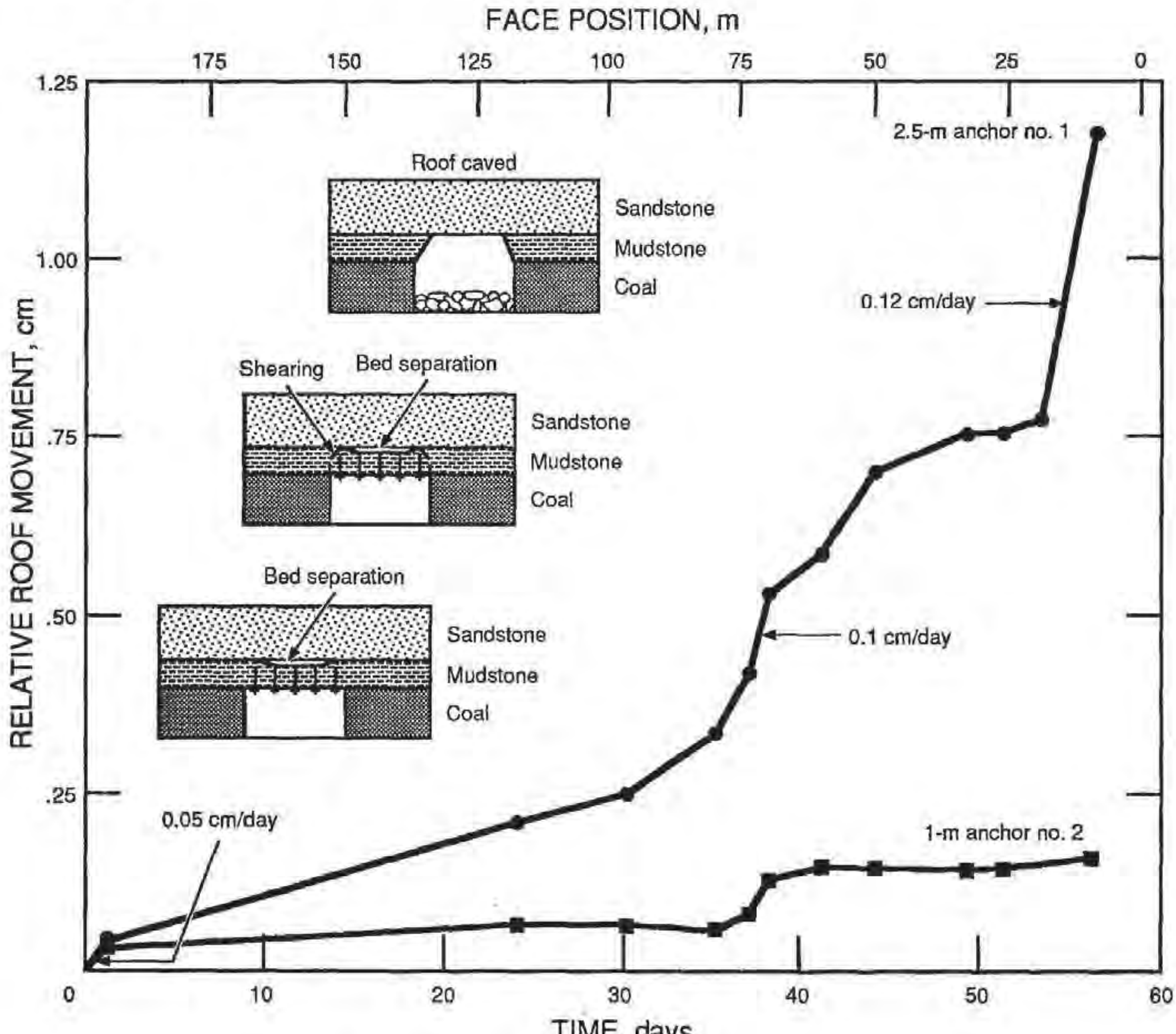

Figure 4.—Relative mine roof movement history for a longwall gate road.

SEISMIC VELOCITY AND ROOF DEFORMATION

A detailed instrumentation plan was developed to measure changes in seismic velocity patterns in mine roofs and to relate these measurements to roof stability and support requirements. These measurements were completed in a shaley mine roof. The plan consisted of—

- Crosshole seismic surveys at 1-month intervals,
- Biweekly deformation measurements in the mine roof, pillar, and floor,
- Biweekly stress change measurements within the seam, and
- Mapping, corehole observations, and core testing in the mine roof either during monthly monitoring or at the beginning and end of the monitoring program.

The instruments were installed in a three-entry development system using 5.2- by 13.4-m pillars and 5.2-m spans at depths of 430 m. Figure 5 shows the instrument layout, mining geometry, and crosshole seismic layout. Accelerometers were attached to the mine roof and installed in a receiver hole using a setting device. An impact unit was used as the seismic source. A tomographic image of velocity patterns in mine roof was constructed along section B-B′.

An array of extensometers was installed in the test area to measure relative mine roof movements. The extensometers were anchored 1.8 and 3.1 m above the roof. In addition, borehole observations were made at locations B and B′ (figure 5) with a borescope to map fracture propagation in the roof and to observe changes in roof moisture during the monitoring period. Two cores were obtained from the roof so that physical properties at the beginning and end of the monitoring program could be compared. Roof appearance was also mapped to monitor development of fracture patterns.

Seam instruments consisted of vibrating wire stressmeters placed in the coal pillars and the solid block, and rib dilatation pins anchored 0.6, 1.2, 2.1, and 2.7 m into the pillar. These measurements were taken to monitor pillar yielding, but are excluded from this discussion.

Significant changes in seismic wave velocities, amount of roof separation, and number of roof fractures occurred during the monitoring period. Supplementary support, consisting of 2.4-m-long fully grouted resin bolts and straps to control roof deformation, was installed on day 80. Roof and floor movements and pillar dilation were all large, indicating rock failure and complex strata interactions around the mining excavation.

Wave velocities were reduced by 22% at the B intersection and by 15% at midpillar during the 120-day monitoring period. Figure 6 and table 3 demonstrate the calculated changes in dynamic properties and relative roof deformation.

Table 3.—Calculated changes in dynamic properties

Factor	*Change, %*
Seismic velocity	21
Maximum amplitude	22
Dominant frequency	48
Deformation modulus	51
Poisson's ratio	125

A preliminary relationship between velocity changes and supplementary support requirements may be established for this mine using these measurements. On day 80, wave velocities were reduced by approximately 17% at the intersection because of increased fracturing and possible roof destressing (Maleki, 1993b). The roof had deformed 60 mm since development. Changes in wave velocity greater or equal to 15% may be used as a criterion for allocating supplementary support.

ROOF STRESS PATTERN

Stress measurements can be a valuable technique for analyzing stress concentrations, destressing, and failure zones in a mine roof when these measurements are compared with expected stress patterns calculated with elastic models. Recent overcoring stress measurements in two vertical holes drilled in a coal mine roof illustrate the use of full stress measurement profiles to assess failure zones and support requirements (Maleki and others, 1994). This analysis differed from conventional measurements for the quantification of the stress field.

The measurements were taken along the main entries of a Colorado mine under a high horizontal stress field. Failure in the mine roof is influenced by both stress concentrations in the mine roof and variations in strength and stiffness of roof rocks. The roof consists of thinly bedded siltstones; massive, fine-grained sideritic siltstones that grade laterally to dark gray limestone; and sandstones.

Figure 7 presents expected stress conditions in (*A*) an elastic mine roof and (*B*) a roof with both elastic and inelastic (brittle and delamination) zones. These generic

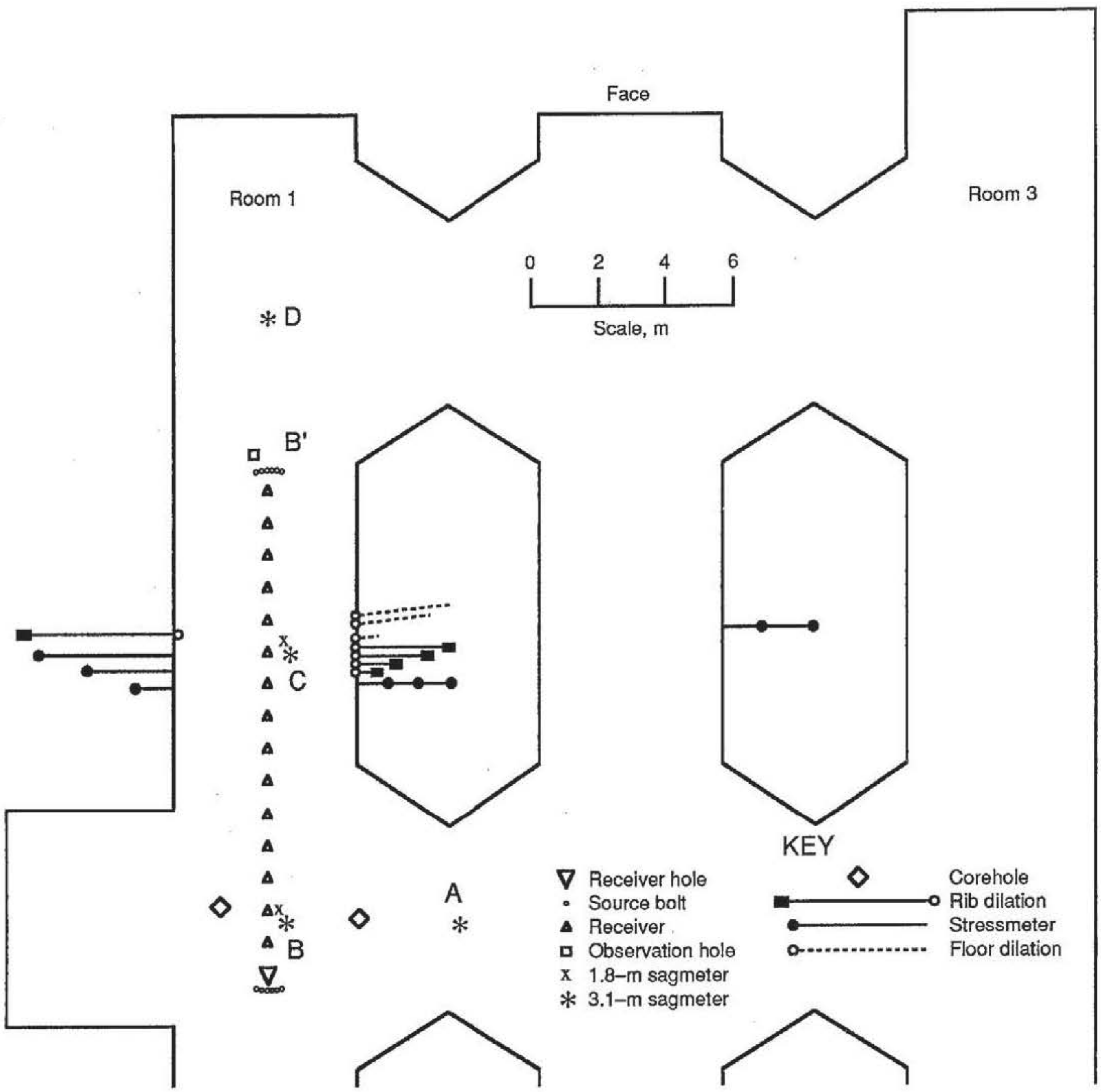

Figure 5.—Instrument layout and face position for mine roof seismic application.

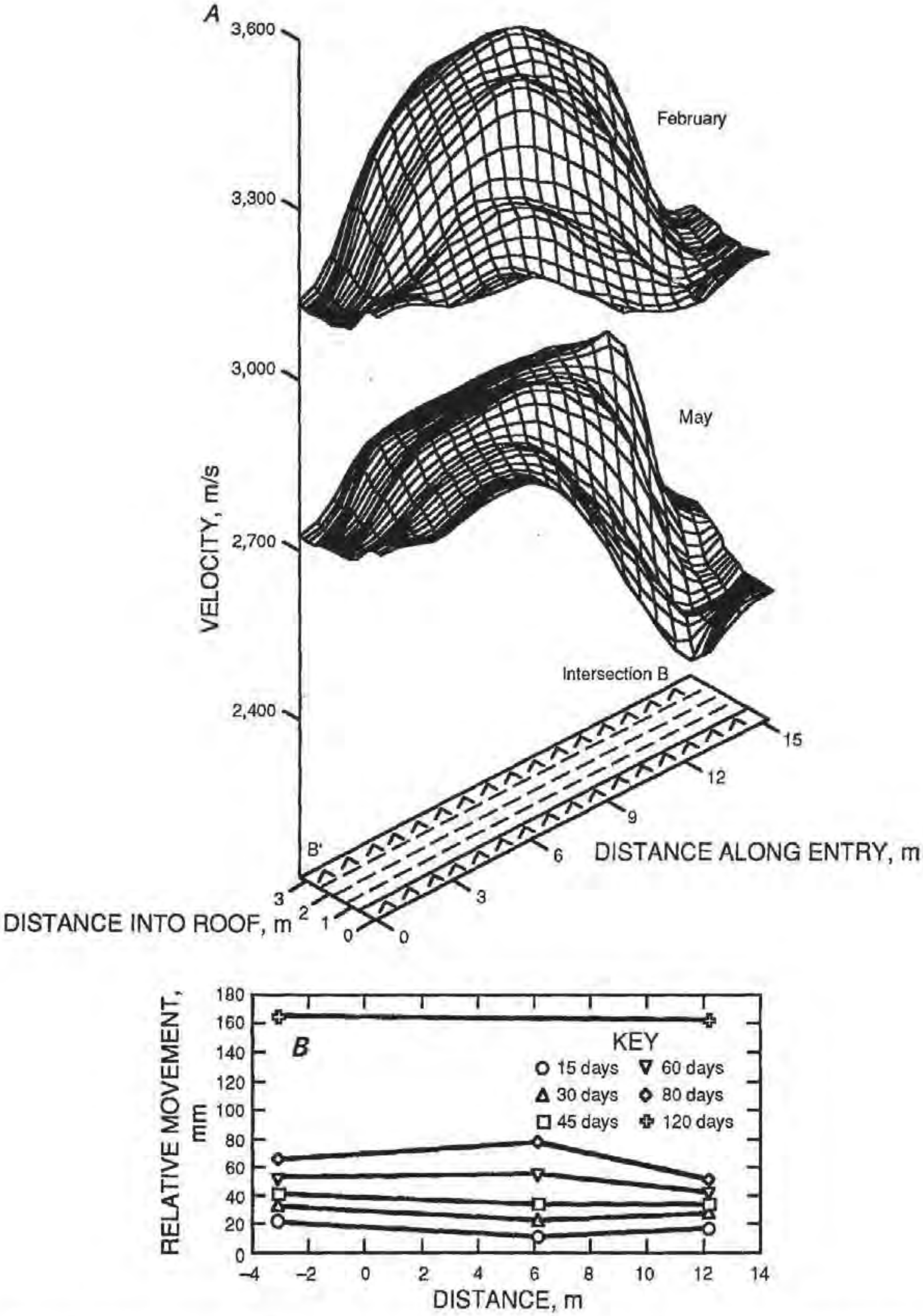

Figure 6.—History of roof velocity and deformation along B-B′ during 120-day monitoring period. ***A*, Velocity; *B*, deformation.**

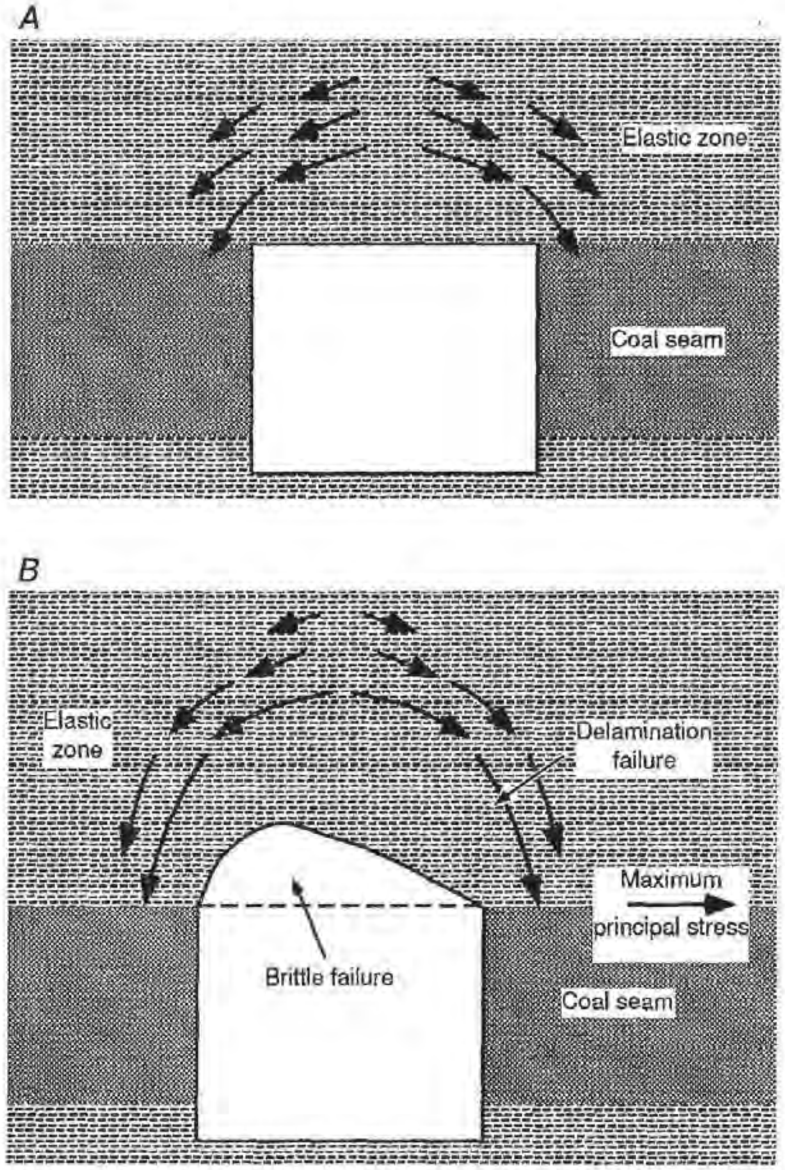

Figure 7.—Principal stresses in mine roof for (*A*) elastic and (*B*) inelastic strata conditions.

models were developed using underground observations, stress measurements, and comparison of the results to numerical models with both elastic and inelastic material behaviors. In the elastic roof (7*A*), the principal stresses concentrate near the immediate mine roof, whereas within the brittle/laminated roof (7*B*), the stresses shift deeper into the roof as a result of failure and partial destressing.

Figure 8 presents the maximum (P) and minimum (Q) measured horizontal stress profiles in the mine roof, supporting the generalized models of figure 7. Figure 8*B* suggests that partial failure in the mine roof extends to a distance of 3 m. This zone requires support and reinforcement to prevent time-dependent collapse of the immediate roof.

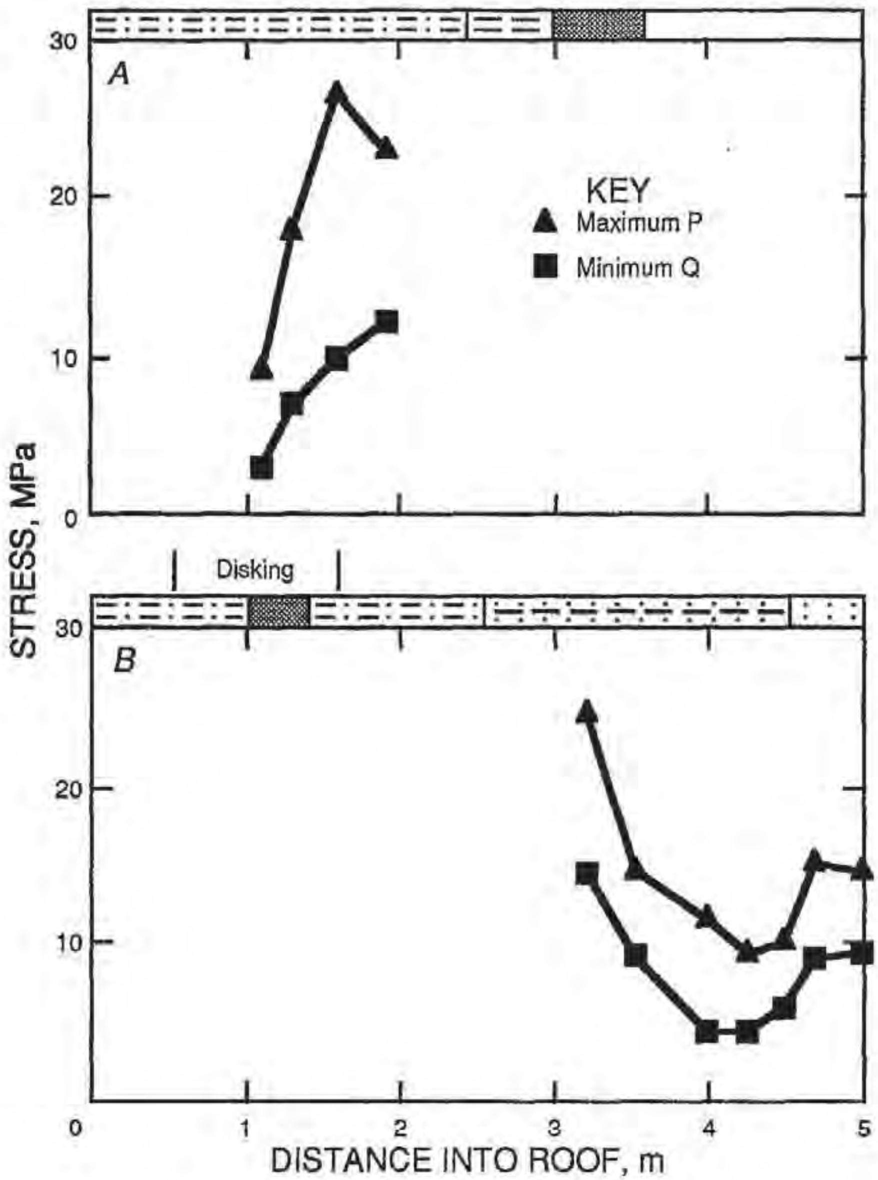

Figure 8.—Measured horizontal stress profiles in mine roof. A, Elastic roof; B, Inelastic immediate roof.

CONCLUSIONS

Practical applications of three methods of evaluating structural stability are presented. Preliminary stability criteria were developed using extensive measurements obtained during the last decade from ten U.S. mines. These methods involve measuring changes in deformation, fracturing, and stress conditions to infer structural stability.

Obtaining deformation measurements is simple, inexpensive, and reliable. These measurements can be used quickly to assess structural stability, thereby enhancing mine safety and improving the decisionmaking process. Measurements of dynamic properties can provide a precise assessment of rock fracturing and support requirements along the entire length of an area of interest. Obtaining these measurements is more costly than obtaining deformation measurements. Therefore, this method is most suitable for detailed structural stability evaluations. Stress profiling can be achieved simply during measurement of far-field horizontal stresses, providing helpful information on strata inelastic behavior and support requirements. This method is most useful for mines experiencing stress-induced stability problems.

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BUREAU OF MINES

Cover Photograph: The U.S. Bureau of Mines has developed highly practical technologies for maintaining effective ground control in the hazardous tailgate entries of longwall mining systems, which will significantly improve the safety of the Nation's underground mineworkers. *(Photo: Alan A. Campoli, Pittsburgh Research Center, U.S. Bureau of Mines)*

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