SUMMARY OF FIELD MEASUREMENTS OF ROOF BOLT PERFORMANCE

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ABSTRACT

During the 1990s, the former U.S. Bureau of Mines conducted a number of field studies in which the performance of different types of roof bolts were evaluated in different geologic environments. The studies used a standard suite of measurements, including multipoint extensometers, strain-gauged roof bolts, and roof bolt load cells. The sites were chosen to investigate the effect of a variety of parameters, including installed tension, bolt capacity, grout annulus, and horizontal stress orientation. Although not fully successful, the measurements provided valuable insights into each of these issues. They also showed that instrumentation and monitoring have important advantages over observational methods for comparing the performance of different roof bolting systems.

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INTRODUCTION

Roof bolts interact with the ground to create a reinforced rock structure. The mechanics of this interaction are difficult, if not impossible, to replicate in the laboratory. Field studies are essential to developing an understanding of how factors such as bolt tension, bolt length, bolt capacity, and resin annulus contribute to the support of real rock masses. Detailed measurements of bolt loads and roof movements can provide the information necessary to build conceptual and numerical models of supported mine roof.

Field studies are also the only way to compare the overall effectiveness of different roof bolt systems. In the United States, such comparisons are usually made by visual observations rather than by measurements. If an area supported by one type of bolt experiences less roof degradation or fewer roof falls than an area supported by another type, then the first bolt is deemed superior [Stankus 1991]. This observational approach, however, has limitations. Often, significant roof movements can occur without visual evidence at the roof line. Waiting to see how many roof falls occur can be expensive, particularly if large areas of the mine were supported with a particular bolt before its inadequacies became apparent. Again, instrumentation can provide an alternative. Measurements can show that bolts are overloaded or that the roof is becoming unstable long before there is any visual evidence.

Studies of roof bolt behavior have a long history in the United States. Some of the classic early work with strain-gauged resin bolts was performed by Karabin and Debevec [1976] and Haas [1981], followed by Serbousek and Signer [1987] and Signer [1990]. Other insights regarding the interaction between roof bolts and the rock mass came from researchers in Australia [Gale 1991; Hurt 1992].

In the early 1990s, the former U.S. Bureau of Mines (USBM) embarked on a major program of roof bolt field studies. One group of studies focused on the behavior of fully grouted, nontensioned resin bolts and is reported by Signer [2000]. The second group of studies, which is described here, had two main goals:

1. To study fundamental aspects of roof bolt performance by comparing different types of bolts in a variety of geologic environments; and
2. To develop an effective instrumentation plan for evaluating roof bolt systems at a particular site.

Ultimately, studies were conducted at 12 sites in 7 mines (mines A through G; see table 1). Most of the studies were conducted under cost-sharing Memorandums of Agreement between the USBM and cooperating coal companies. Unfortunately, the program ended in 1995 when the closing of the USBM resulted in reduced funding for ground control research.

Table 1.—Summary of field studies

Mine	Reference	State	Seam	Depth, m (ft)	Mining method	CMRR	Bolt type	Bolt capacity, kN (tons)	Length, m (ft)	Comments
A	Mucho et al. [1995]	PA	Lower Kittanning	275 (900)	Longwall	48	Fully grouted resin	200 (22.5)	1.8 (6)	Two different hole sizes.
B	Mucho et al. [1995]	PA	Sewickley	180 (600)	Longwall	40	Point-anchor tension	200 (22.5)	2.1 (7)	No instrumented bolts.
C	Mucho et al. [1995]	KY	Kellioka	130 (400)	Room-and-pillar	47	Fully grouted resin	115 (13)	1.8 (6)	No instrumented bolts.
							Fully grouted tension	115 (13)	1.8 (6)	No instrumented bolts.
D	Mucho et al. [1995]; Mark et al. [1998].	PA	Pittsburgh	250 (800)	Longwall	35	Point-anchor tension	135 (15)	2.5 (8)	—
							Point-anchor tension	85 (9.5)	2.5 (8)	Poor anchors reduced capacity.
E	Mark et al. [1998]	PA	Pittsburgh	250 (800)	Longwall	35	Fully grouted resin	115 (13)	1.5 (5)	No instrumented bolts.
							Point-anchor tension	150 (16.5)	2.5 (8)	—
F	Signer et al. [1993].	AL	Blue Creek	670 (2,200)	Longwall	47	Fully grouted resin	100 (11.5)	1.8 (6)	—
							Point-anchor tension	160 (17.5)	1.8 (6)	—
G	Campoli et al. [1996]	PA	Lower Kittanning	100 (300)	Room-and-pillar	50	Point-anchor tension	100 (11.5)	1.5 (5)	Third pattern of mixed bolts.
							Fully grouted resin	75 (8.5)	1.8 (6)	No instrumented bolts.

NOTE.—Point-anchor tension bolts were all resin-assisted mechanical bolts.

STANDARD INSTRUMENTATION

The studies usually began with an assessment of roof geology using the Coal Mine Roof Rating (CMRR). The CMRR rates the structural competence of the roof and allows the roof at different sites to be compared on a single scale [Molinda and Mark 1994]. Instrumentation sites also usually included a 1-in (25-mm) diameter, 16-20 ft (5-6 m) vertical borehole for logging with a stratascope. Stratascope surveys provide a means to assess interfaces, bedding, or other geological features; identify general roof rock lithology; and observe bed separations.

Several means were used to monitor support loads in the studies. For fully grouted resin bolts, strain gauges were mounted in slots machined in the roof bolts [Signer 2000]. For resin-assisted point-anchor systems, loads were monitored using electronic or hydraulic load cells mounted between the plate and the bolt head. Further details may be found in the original reports [Signer et al. 1993; Mucho et al. 1995; Campoli et al. 1996; Mark et al. 1998].

Roof movements were monitored using extensometers, convergence stations, and observation holes. One to three extensometers were included in each instrumented area depending on the detail of roof movement required by the investigation. Most of the studies used the Sonic Probe type of extensometer. The Sonic Probe measures the distance between magnetic anchors placed in a 38-mm (1.5-in) diameter borehole to a claimed accuracy of 0.025 mm (0.001 in). As many as 20 anchors can be placed in a 6-m (20-ft) long vertical borehole.

The data from the extensometer locations can be presented as deformation in each interval or as percent strain. Strain is determined by dividing the movement between the anchor intervals by the original length of the interval. Multiplying this strain by 100 yields percent strain for the interval. A rule of thumb developed abroad is that 1% strain measured above the bolts is an unstable condition [Hurt 1992]. The concept is that once a roof bed experiences 1% strain, it fails and can no longer carry horizontal stress, thus forcing the stresses to move higher into the roof. If a roof bed fails above the bolts, it may indicate a loss of ground control. Large roof strains within the bolted horizon are of much less concern. One goal of the studies was to test whether the concept of roof strain was useful for U.S. conditions.

In the course of the studies, a standard instrumentation plan evolved (figure 1). Unfortunately (as the comments in table 1 indicate), it was not possible to install all of the instrumentation at every site. No instrumented bolts were used at five of the sites, and simple three-point extensometers were used at two others.

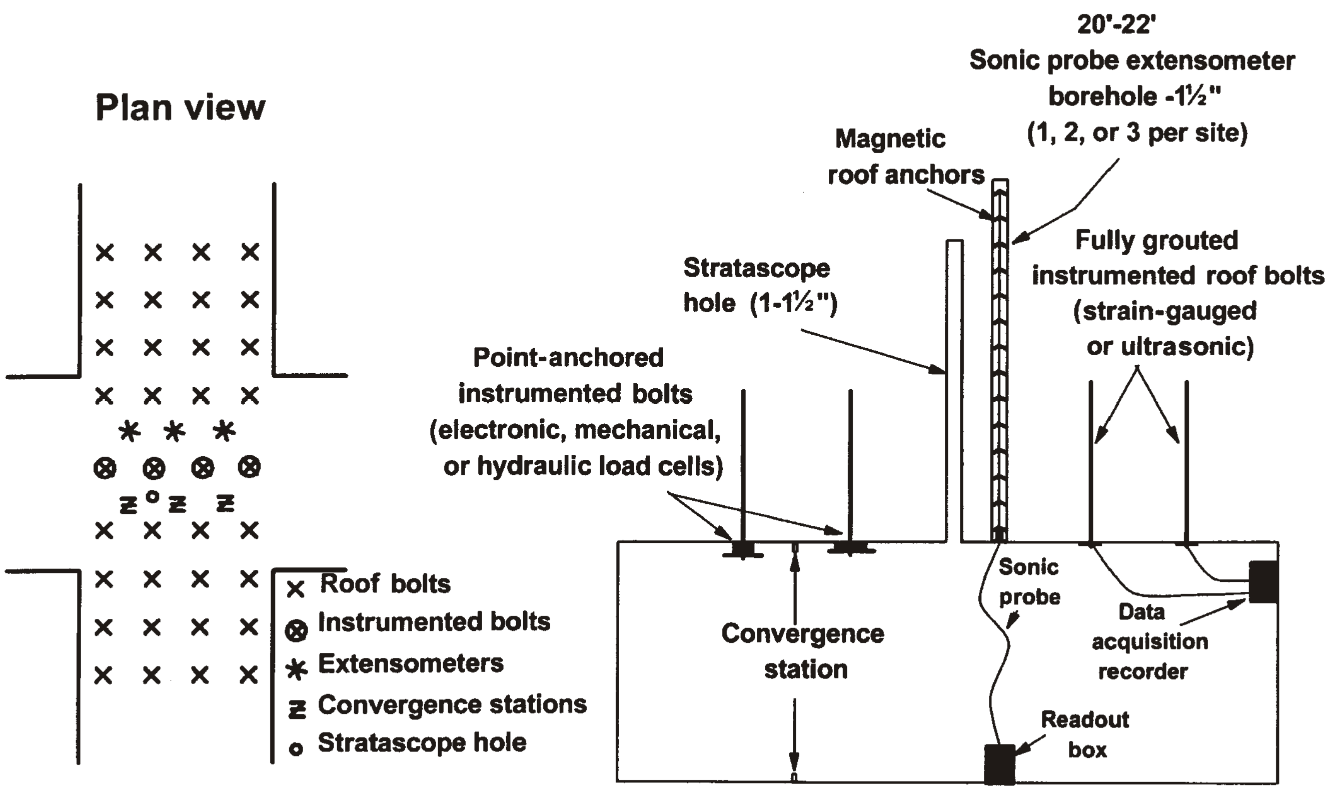

Figure 1.—Standard instrumentation for field evaluation of roof bolt performance.

DISCUSSION

Brief descriptions of the field sites and the individual results are included in the appendix to this paper. Ultimately, the number of sites was too small to provide definitive answers to any of the fundamental questions about bolt mechanics. Moreover, they do not allow a multivariate analysis, in which interactions between the geologic and design factors might be assessed. Nevertheless, the studies provided some valuable insights into the effects of these factors on roof bolt performance, which are discussed below.

GEOLOGY

The tests were performed in a wide variety of geologic environments, with roof rocks that included coal, underclay, shale, "stack rock" sandstone, and siltstone. The CMRR values shown in table 1, however, indicate that the sites can be classified into two groups. The CMRR was 40 or less at five of the sites (mines B, D, and E); the roof there could be described as "weak." At the remaining seven sites, the CMRR was between 47 and 50, which means that the roof strength was "moderate."

Roof strains in excess of 1% were measured above the bolt anchorage at five sites, although no roof falls occurred. Three of these were weak roof sites in the vicinity of longwalls, indicating that weak roof is more likely to experience large roof movements than moderate roof. Large strains were measured within the bolted horizon at many sites in all types of roof, however. No clear differences in bolt loading patterns emerged among the different geologies.

HORIZONTAL STRESS

Horizontal stress was clearly a major factor at many of the sites. At two mines (B and C), extensometers were placed in entries and crosscuts that were oriented in "good" and "bad" directions relative to the horizontal stress. In both cases, the roof strains were at least three times greater in the "bad" direction.

Several studies showed the effect of the "horizontal stress abutment" due to longwall mining that has been described by Mark et al. [1998]. The sites at mines A, D, and F were located in longwall gate entries that were subjected to horizontal stress abutments. Large roof movements were measured at each site, and the majority of the instrumented roof bolts approached or exceeded the yield point. In contrast, the sites at mine E were located in a stress shadow, and no new roof movements occurred as the longwall face approached. In fact, the bolt loads even decreased slightly!

INSTALLED TENSION

One of the most controversial issues in roof bolting is the im-portance of installed tension. Three studies compared tensioned to nontensioned bolts, but the results were ambiguous.

The study at mine C compared tensioned and nontensioned fully grouted bolts. Greater movements were measured at the nontensioned site, primarily within the bolted horizon. The presence of a preexisting cutter in the roof at the nontensioned site, however, may have influenced the results.

At mine G, resin-assisted point-anchor tensioned bolts were compared with nontensioned fully grouted resin bolts. At a third site, the fully grouted bolts were supplemented by some resin-assisted point-anchor bolts. The point-anchor bolts were 1.5 m (5 ft long), while the fully grouted bolts were 1.8 m (6 ft) long. Out of a total of seven instrumented intersections, two experienced strains in excess of 1% above the bolts. One was in the point-anchor site, but the other was one where the fully grouted bolts had been supplemented by point anchors. Overall, the differences among the three bolting systems were probably not statistically significant.

The study at mine F was probably the most informative of the three. Here, the resin-assisted point-anchor bolts clearly provided better roof control than the nontensioned, fully grouted bolts. The point-anchor bolts were also 60% stronger, however, and their greater capacity may have accounted for their better performance. More surprising were the bolt load measurements. These showed that although the fully grouted bolts were installed without tension, within days their loads were equal to or greater than those of the point-anchor bolts. The loadings on the two systems continued to increase at approximately the same rate as mining progressed, up until the point where most of the fully grouted bolts were loaded beyond their yield point.

BOLT CAPACITY

As previously mentioned, the study at mine F found that the higher capacity bolts performed better, although installed tension may have been a contributing factor. However, mine F subsequently switched to higher capacity, nontensioned, fully grouted bolts and used them successfully for many years.

The study at mine D provided a clearer association between greater capacity and better roof control. Here, the two types of resin-assisted point-anchor tension bolts that were compared were nearly identical except for the length of the resin used to assist the mechanical shell. The bolts with the shorter length of resin proved to have 40% less capacity due to inadequate anchorage. The measurements showed that both types of bolts loaded approximately in tandem until the short-anchor bolts slipped. Then the loads on the short-anchor bolts diminished while the roof movements accelerated. Ultimately, a 6% roof strain was measured above the anchorage. In contrast, the loads continued to increase on the long-anchor bolts, and roof control was maintained.

The mine D study also demonstrated the value of instrumentation in evaluating different bolt systems. There was no visible difference between the sites, but the measurements clearly showed that the performance of the short-anchor bolts was inadequate. Also, it was evident that measurements of both roof movement and bolt load were necessary to tell the complete story. Larger roof strains by themselves could have meant that the roof was just more aggressive, while reduced bolt loads alone might have signified more stable roof. But the combination clearly signaled that the bolts had slipped and had lost control of the ground.

BOLT LENGTH

Different lengths of bolts were studied at mines E and G. No meaningful comparison was possible at mine E because all of the sites were stable. At mine G, although the greatest roof strains were measured where the shorter bolts were used, the results were probably not statistically significant.

RESIN ANNULUS

The study at mine A was designed to investigate whether a "reduced annulus" (a smaller difference between the bolt diameter and the diameter of the bolt hole) would improve the performance of the primary bolting system (see Mark [2000] for a discussion of the importance of annulus to fully grouted resin bolt performance). The instrumented bolts were installed with annuluses of 7 mm (0.28 in) and 3 mm (0.12 in), but no significant differences in the bolt-loading histories were observed.

INTERSECTIONS VERSUS ENTRIES

Statistics clearly show that intersections, because of their greater spans, are significantly more prone to roof falls than entries. Measurements from the field studies provide further confirmation. At mine D, roof strains in the intersections were typically twice as great in the intersections, although the bolt loadings were approximately the same in all locations. At mine F, the bolt loads were typically 25% higher in the intersections, while the measured roof sags were similar to those in the entries.

BOLT LOCATION

The field studies found that, in general, the bolts with the highest loads were located in the center of the entry or intersection. When a cutter was present, such as at mines A, F, and G, the bolts nearest the cutter were likely to be the most heavily loaded.

CONCLUSIONS

The field studies were only partially successful in achieving their goals. Of the bolt design parameters that were evaluated, only bolt capacity seemed to clearly affect roof stability. The results concerning installed tension, bolt length, and resin annulus were all ambiguous.

On the other hand, the studies confirmed that greater roof bolt loads and more severe roof movements are likely to occur—

- In intersections;
- Near roof cutters;
- In entries perpendicular to the principal horizontal stress; and
- In areas subjected to horizontal stress concentrations.

It seems that in many cases roof stability could be improved by selectively installing stronger and/or longer bolts in these areas.

Finally, the standard instrumentation plan was shown to be an effective approach to evaluating different roof bolting systems. It provides an unequaled look into the performance of the supports and their interactions with the roof. Hopefully, mines will continue to use the instrumentation to help address their roof support issues and at the same time improve our fundamental knowledge of how roof bolts work.

REFERENCES

Campoli AA, Rebuck D, Mucho TP, Molinda GM [1996]. State-of-the-art room and pillar mining in the Kittanning Coalbed. In: Ozdemir L, Hanna K, Haramy KY, Peng S, eds. Proceedings of the 15th International Conference on Ground Control in Mining. Golden, CO: Colorado School of Mines, pp. 269-285.

Gale WJ [1991]. Strata control utilizing rock reinforcement techniques and stress control methods in Australian coal mines. The Mining Engineer (U.K.) *Jan*:247-253.

Haas CJ [1981]. Analysis of rockbolting to prevent shear movement in fractured ground. Min Eng *June*:691-704.

Hurt K [1992]. Rockbolting design in UK coal mines. In: Proceedings of Eurock 92. London, U.K.: Thomas Telford, paper No. 71, pp. 414-419.

Karabin GJ, Debevec WL [1976]. Comparative evaluation of conventional and resin bolting systems. U.S. Department of the Interior, Mine Enforcement and Safety Administration, IR 1033.

Mark C [2000]. Design of roof bolt systems. In: New Technology for Coal Mine Roof Support. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Mark C, Mucho TP, Dolinar DR [1998]. Horizontal stress and longwall headgate ground control. Min Eng *Jan*:61-68.

Molinda GM, Mark C [1994]. The Coal Mine Roof Rating (CMRR): a practical rock mass classification for coal mines. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 9387.

Mucho TP, Mark C, Zelanko JC, Compton CS [1995]. Roof support performance in high stress conditions. In: Peng SS, ed. Proceedings of the 14th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 30-38.

Serbousek MO, Signer SP [1987]. Linear load-transfer mechanics of fully grouted roof bolts. Washington, DC: U.S. Department of the Interior, Bureau of Mines, RI 9135.

Signer SP [1990]. Field verification of load transfer mechanics of fully grouted roof bolts. Washington, DC: U.S. Department of the Interior, Bureau of Mines, RI 9301.

Signer SP [2000]. Load behavior on grouted bolts in sedimentary rock. In: New Technology for Coal Mine Roof Support. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Signer SP, Mark C, Franklin G [1993]. Comparison of active versus passive bolts in a bedded mine roof. In: Peng SS, ed. Proceedings of the 12th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 16-23.

Stankus JC [1991]. Tensioned point anchor resin system vs. non-tensioned fully grouted rebar–two case studies. In: Peng SS, ed. Proceedings of the 10th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 65-75.

APPENDIX.—INDIVIDUAL FIELD STUDIES

MINE A

Mine A was located in Cambria County in central Pennsylvania [Mucho et al. 1995]. This multiple-seam longwall mine closed in 1995 largely because of a long history of ground control problems related to horizontal stress.

The goal of the study was to investigate the effect of a reduced annulus on the bolt-loading history. The annulus was reduced from 7.3 mm (0.29 in) to 3 mm (0.11 in) by installing a No. 7 bolt 20.5 mm (0.804 in) in a 26-mm (1-1/32 in) hole rather than the standard 35-mm (1-3/8-in) hole.

The instrumentation consisted of nine instrumented (strain-gauged), fully grouted, grade 75, No. 7 roof bolts installed in the normal bolting pattern (figure A-1). As shown in the figure, the bolts were alternately installed in reduced annulus and normal annulus bolt holes by position in the entry. A centrally located sonic roof extensometer and a stratascope investigation hole were also included at the site.

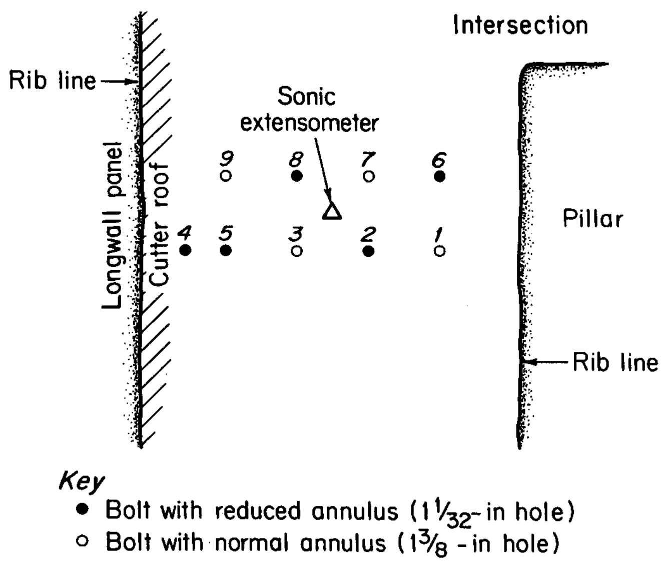

Figure A-1.—Map of study site at mine A.

Roof geology consisted of approximately 1.5 m (5 ft) of thinly laminated shale under a coarse sandstone consisting of 0.15- to 0.6-m (6-in to 2-ft) beds with thin coal streaks separating the beds. The CMRR value for the area was 48. The overburden in the study area was 900 ft (275 m).

As shown in figure A-1, a roof cutter (rock shear failure) formed along the left (panel side) rib coincident with mining and prior to the instrumentation or other supports being installed. Very little roof movement was measured initially, however. Nine days after installation there had only been a few millimeters of movement slightly above the bolts. After several weeks, however, the roof within the development section began to "work" (audible noise, dripping, etc.), and workers had to be called to the mine to set supplemental supports throughout the section, including the instrumented area, to prevent possible roof collapse. The extensometer showed that a movement of slightly over 13 mm (0.5 in) had occurred above the bolts and near the bolt top anchorage zone at the shale/sandstone interface (figure A-2).

The bolt loads during development were a function of the position of the bolt within the entry and relative to the roof cutter failure. Bolts Nos. 3 and 8, in the center of the entry on the same side as the cutter, experienced the highest peak and average loads. Loads on these bolts exceeded the yield strength of the steel (>200 kN (45,000 lb)) within 2 weeks of installation. Next heavily loaded were the side bolts next to the cutter (Nos. 5 and 9). It was assumed they were slightly lower than bolts Nos. 3 and 8 due to being installed in the failing rock of the cutter. The reduced annulus bolts experienced loads only slightly higher than the normal annulus bolts.

As the longwall approached, there was a total of approximately 31 mm (1.25 in) of total deformation. All locations experienced increases in load due to the front abutment of the longwall. Again, annulus appeared to have little effect on either the magnitude, distribution, or timing of bolt loading.

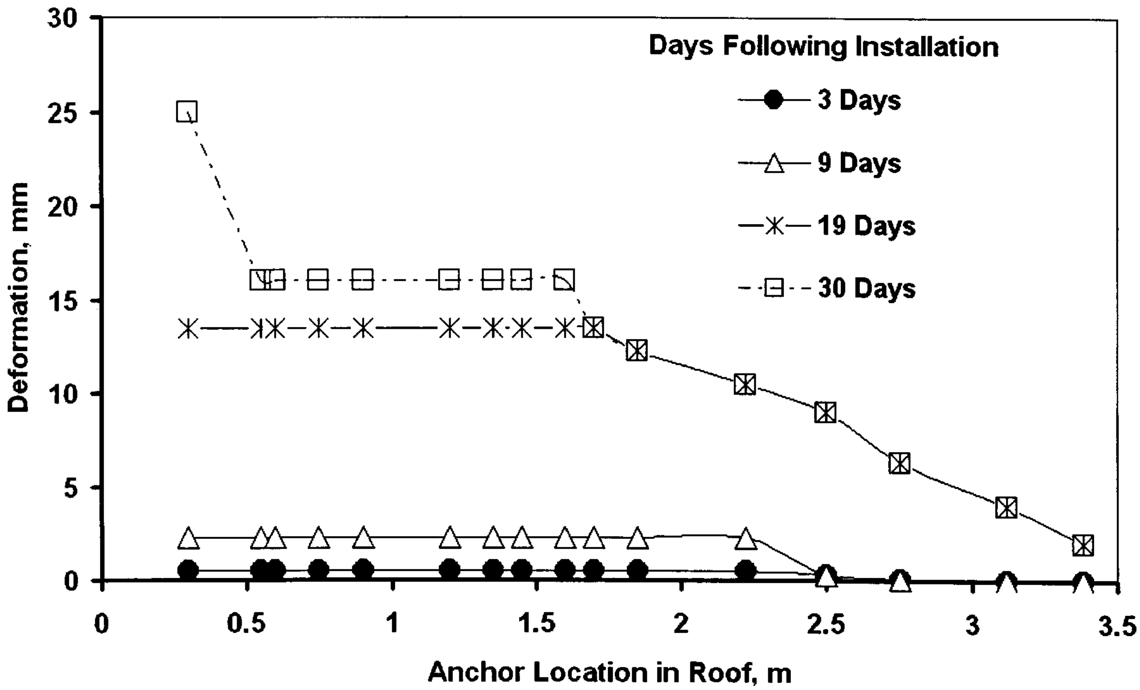

Figure A-2.—Roof deformations measured at mine A.

MINE B

Mine B was located in Greene County in southwestern Pennsylvania [Mucho et al. 1995]. This longwall mine, now also closed, operated in the Sewickley Coalbed. The mine also had a long history of ground control problems associated with horizontal stress.

The immediate roof in the instrumented area was composed of a black shale approximately 0.3 to 0.9 m (1 to 3 ft) thick, overlain by a dark gray shale or layered shale, sometimes with sandy bands or grading into a silty or sandy shale. Pronounced jointing was prevalent in the roof. Overburden in the area was approximately 180 m (600 ft). Stress mapping determined that the maximum horizontal stress was oriented approximately east-west. CMRR values in the study area ranged from the high 30s to low 40s.

To evaluate the effect of mining orientation relative to the horizontal stress field, extensometers were placed in an east-west entry (the "good" direction) and a northwest-angled crosscut (figure A-3). Due to severely broken ground, extensometers could not be installed in the north-south crosscuts (the "bad" direction) as planned.

The roof in the area of the entry extensometer showed immediate roof flaking and appeared as though it was developing a cutter; this area was rebolted in some places along the entry length. However, as can be seen from figure A-4, the strains were less than 1% and confined to the lower portions of the roof (less than the bolted interval of 2.1 m (7 ft)). Total recorded roof deformation was only approximately 6 mm (0.25 in), and the roof evidently was quite stable despite its appearance.

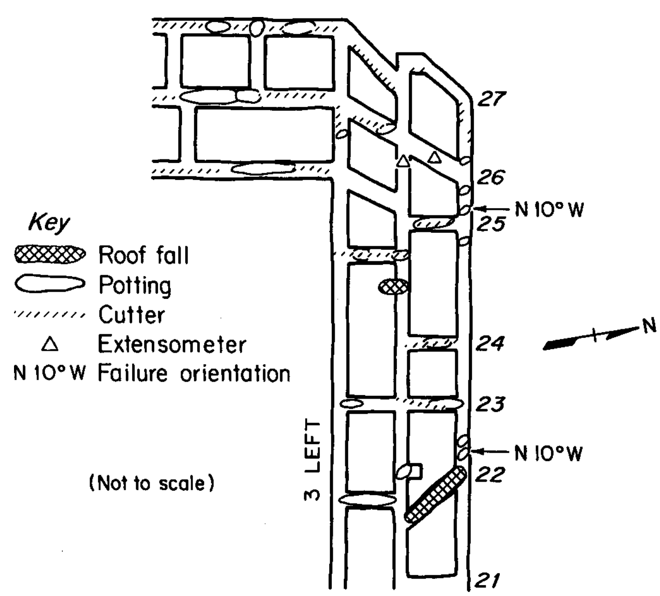

Figure A-3.—Study site at mine B.

The crosscut was far less stable, as evidenced by the strains in the roof within the bolted horizon. Strains were >1% within weeks of development at several locations. By the time the longwall passed, the strains at 2.3 m (7.5 ft), which is above the bolt anchorage zone, had increased to almost 4%. Total roof deformation (sag) at that time was approximately 25 mm (1 in). Despite the large strains, the roof was still standing after the longwall had passed.

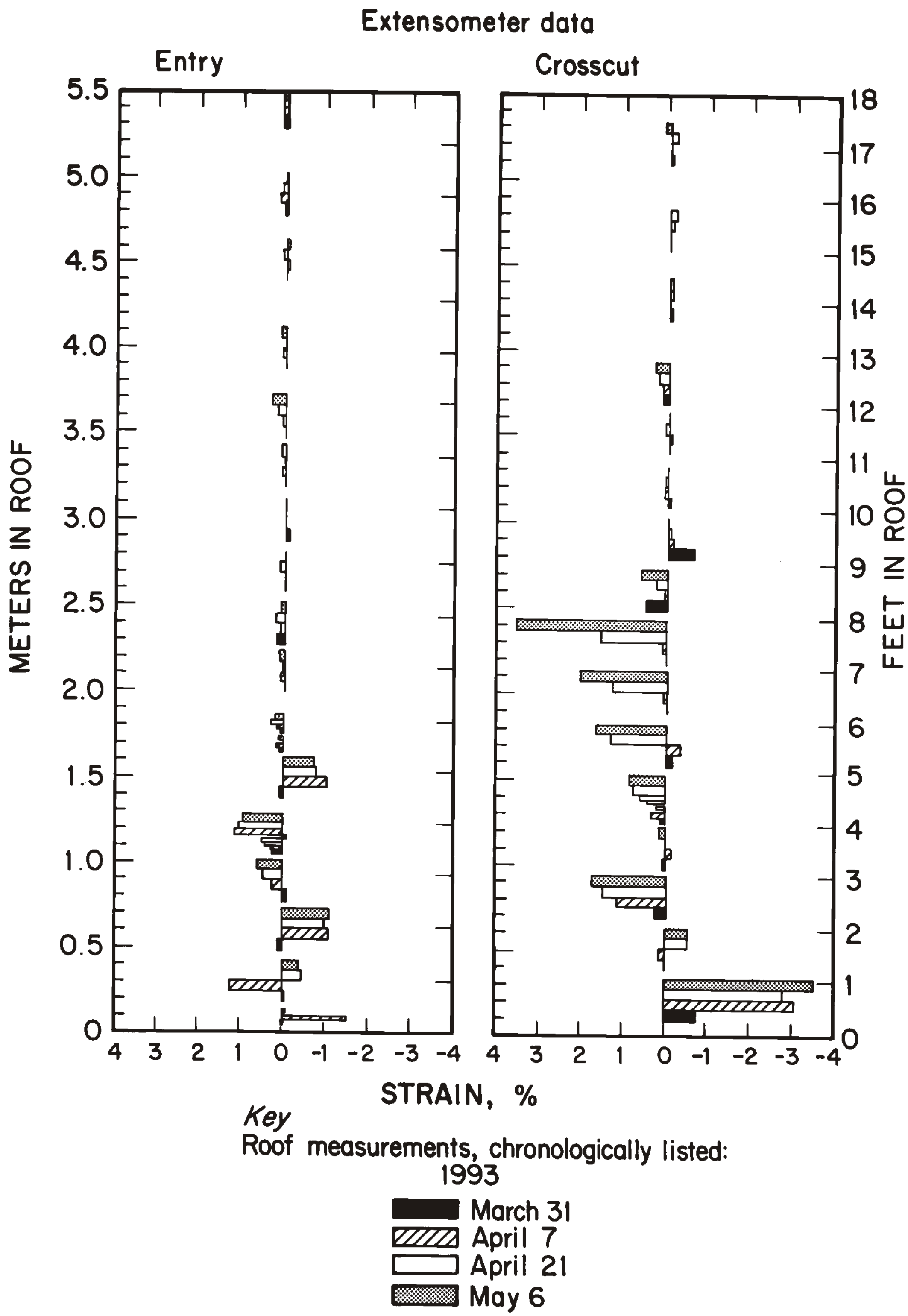

Figure A-4.—Roof deformations at mine B.

MINE C

Mine C was located in Harlan County in eastern Kentucky [Mucho et al. 1995]. This was a drift, room-and-pillar operation mining the Kellioka Coalbed under Black Mountain. Overburden in the study area was 120 m (400 ft). The immediate roof near the study area was a laminated, shaley sandstone, often with coal streaks ("stack rock"). Calculated CMRRs ranged between 54 and 44.

Multipoint roof extensometers were installed in the No. 2 entry, which was supported by 1.8-m (6-ft) tensioned rebar bolts, and in the No. 4 entry, which was supported with 1.8-m (6-ft) fully grouted resin bolts. An adjacent crosscut was also instrumented. The entries were oriented in the "bad" direction approximately perpendicular to the maximum horizontal stress.

A roof cutter developed coincident with mining in the No. 4 entry (the resin bolt area), and a similar cutter developed soon after mining in the No. 2 entry. The extensometers in the resin bolted No. 4 entry detected roof movements within 3 hr of installation. During the next 3 weeks, major roof movements (as much as 7% strain) were recorded within the bolted horizon (figure A-5). Since the cutter developed later in the tensioned rebar area, the roof movements occurred later following mining. The magnitudes of the movements in the tensioned rebar area were also less than the nontensioned fully grouted bolt area, ranging between 1% to 2% strain in the lowest 1.5 m (5 ft) of the roof. Like the fully grouted nontensioned area, no movement was observed above the bolted horizon during the study period.

MINE D

Mine D, located in Greene County in southwestern Pennsylvania, was a longwall mine in the Pittsburgh Coalbed [Mark et al. 1998; Mucho et al. 1995]. Overburden generally ranged from 180 to 300 m (600 to 1,000 ft) at the mine. The immediate roof is typical of Pittsburgh Coalbed geology, alternating relatively weak shales and coals. The CMRR for the study area was 35. The longwall panels at mine D were oriented such that the headgate where the study was conducted was subjected to a horizontal stress abutment.

Bolts from two manufacturers, designated "X" and "Y", were compared in the study. Both were 2.4-m (8-ft) long, 18-mm (0.75-in) diameter, grade 75, two-piece, resin-assisted mechanical-anchor roof bolts. The most obvious difference between the two was that the Y bolts used 0.6 m (2-ft) of resin, while the X version used only 0.3 m (1 ft) of resin with a compression ring. The instrumentation plan used for the two test sections is shown in figure A-6.

All bolts increased load shortly after installation during the development stage; intersection bolts increased the most and center bolts achieved the highest loads (they also were the highest initial set loads).

The maximum load achieved by the short-anchor X bolts averaged 84.5 kN (19,000 lb), but in many cases the load was dropping as the longwall approached. Several Y bolts achieved the yield limit of the steel of 150 kN (33,000 lb), and most continued to increase their load up until the final reading as the longwall face passed (figure A-7). Since the maximum load achieved by the short-anchor bolts was well below the strength of the steel, it appears that the anchors must have been slipping. The most likely explanation is that 0.3 m (1 ft) of resin was insufficient to maintain anchorage in this particular roof rock.

Roof strains measured during the approach of the longwall are shown in figure A-8. At the X bolt stations, roof strains >2% were measured at four locations within the bolted horizon. At one intersection location, a roof strain of 6 was measured *above the bolts*. The X bolts apparently began to lose control of the ground as the horizontal stress concentration developed.

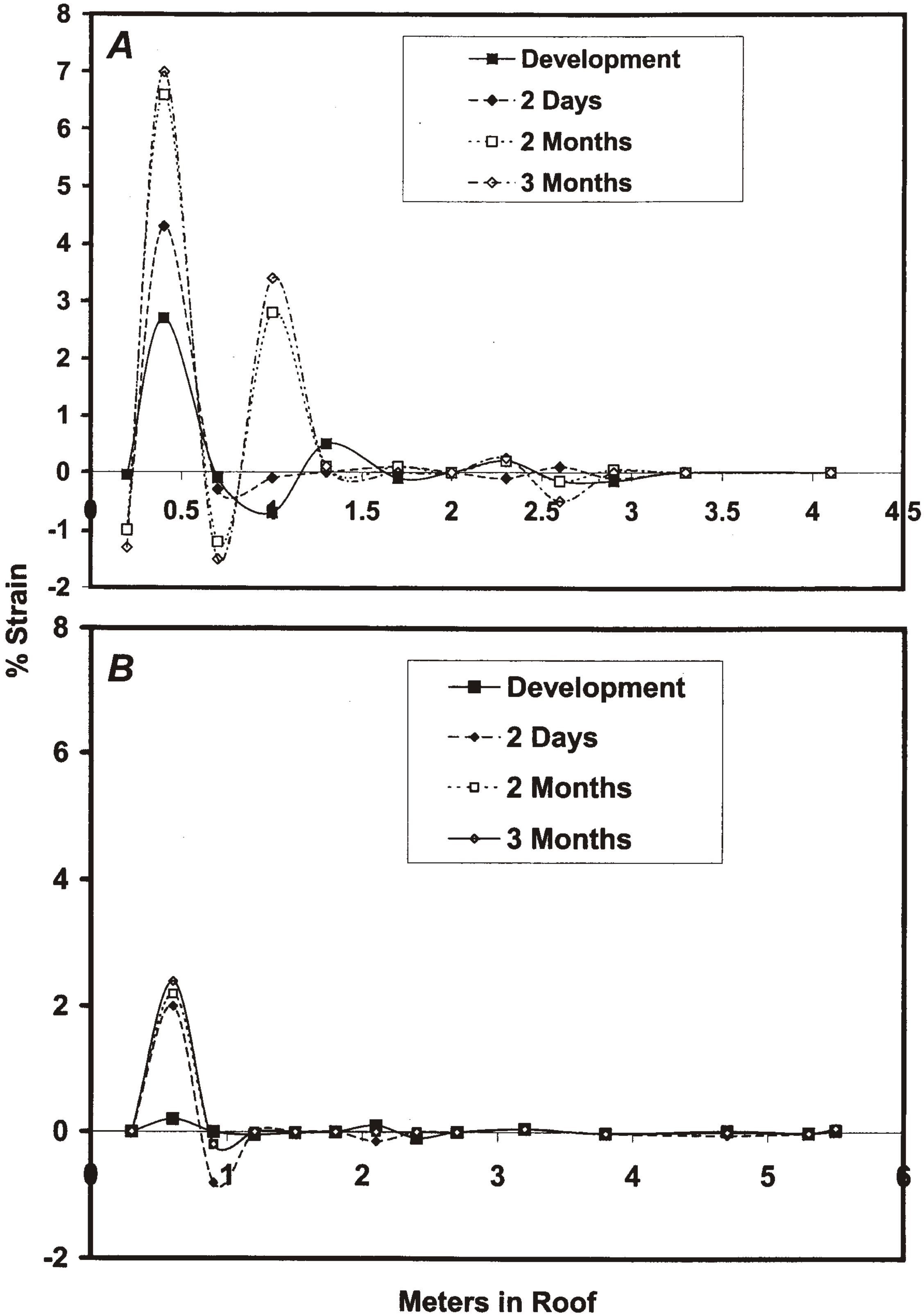

Figure A-5.—Roof strains measured at mine C. ***A*, Resin bolt site; *B*, torque-tension bolt site.**

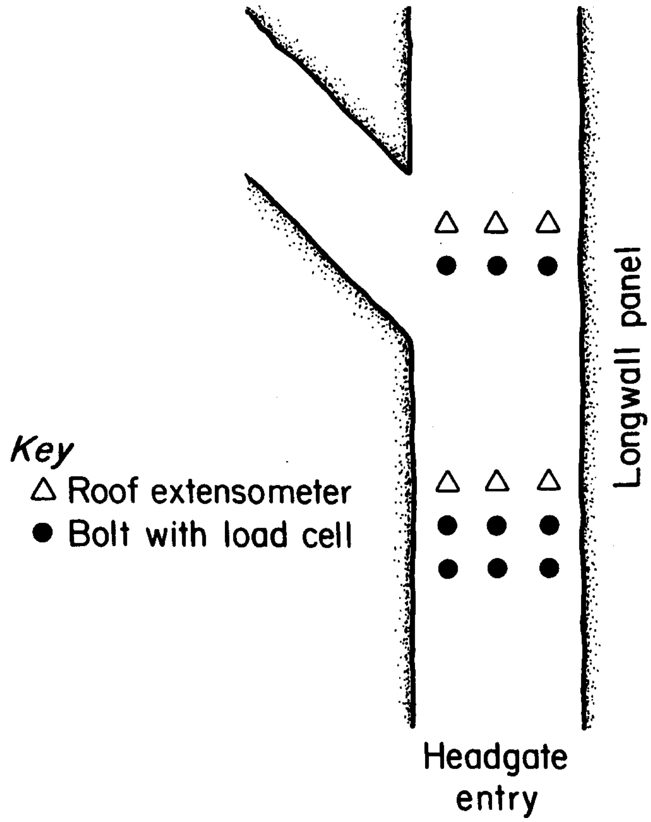

Figure A-6.—Instrumentation plan at mine D.

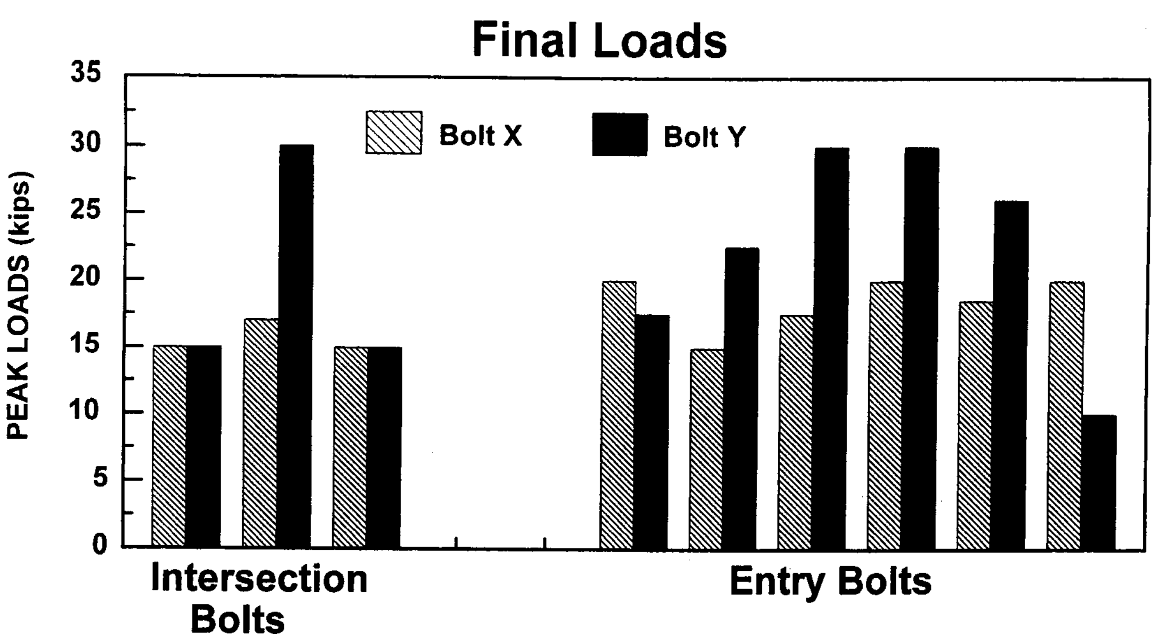

Figure A-7.—Roof bolt loads measured at mine D. Bolts are paired by location (i.e., the first pair shows the intersection right-hand X bolt compared to the intersection right-hand Y bolt.

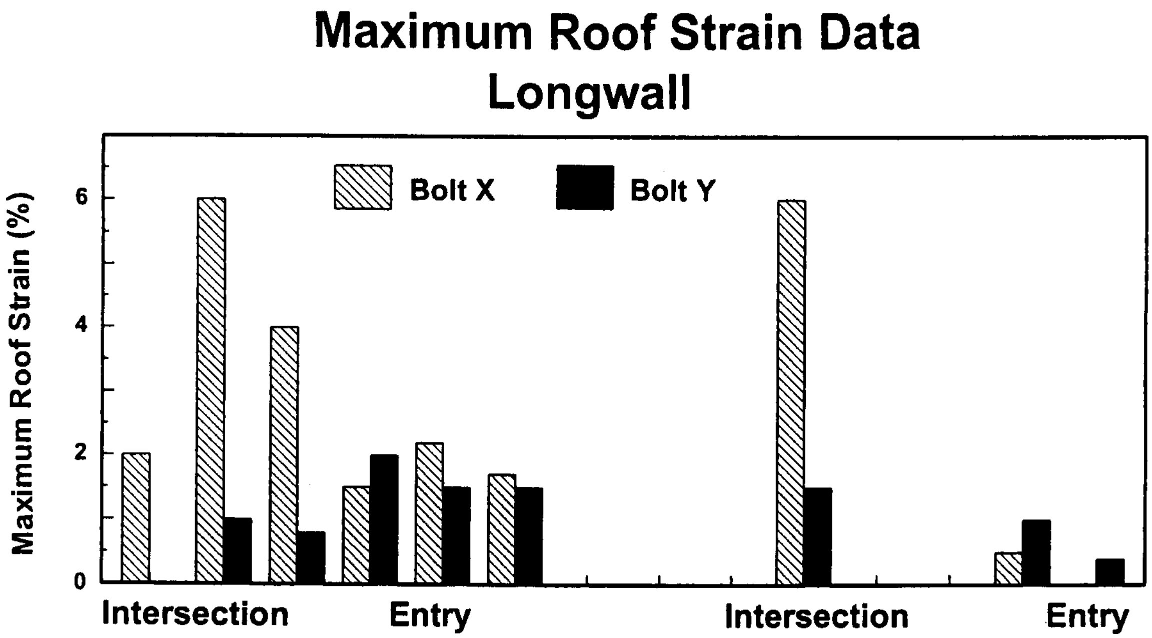

Figure A-8.—Roof strains measured at mine D. The right-hand data show strains measured within the bolted horizon; the left-hand data show strains measured above the tops of the bolts.

MINE E

Mine E was a sister operation to mine D and was similar in most respects [Mark et al. 1998]. One significant difference was that the horizontal stresses are relieved in the headgate by the longwall's stress shadow. Four bolting systems were compared in consecutive intersections at mine E:

- Fully grouted resin bolts, 1.5 m (5 ft) long, 1.4-m (4.5-ft) row spacing;
- Fully grouted resin bolts, 1.5 m (5 ft long), 1-m (3-ft) row spacing;
- Resin-assisted mechanical-anchor bolts, 1.5 m (5 ft) long, 1.4-m (4.5-ft) row spacing; and
- Resin-assisted mechanical-anchor bolts, 2.4 m (8 ft) long, 1.4-m (4.5-ft) row spacing.

The fourth bolting system was essentially identical to that employed at mine E.

Very little change in roof deformation and almost no change in bolt load was observed at any of the four sites as the longwall approached. The maximum increase in roof strain averaged a mere 0.2%, and all of this occurred below the bolt horizon. Final loads on the tensioned bolts ranged between 75 and 135 kN (8 and 15 tons), considerably less than their 150-kN (16.5-ton) yield strength. As the longwall approached, some bolts even decreased load slightly (figure A-9). It appears that relief of the horizontal stress may actually have *enhanced* roof stability!

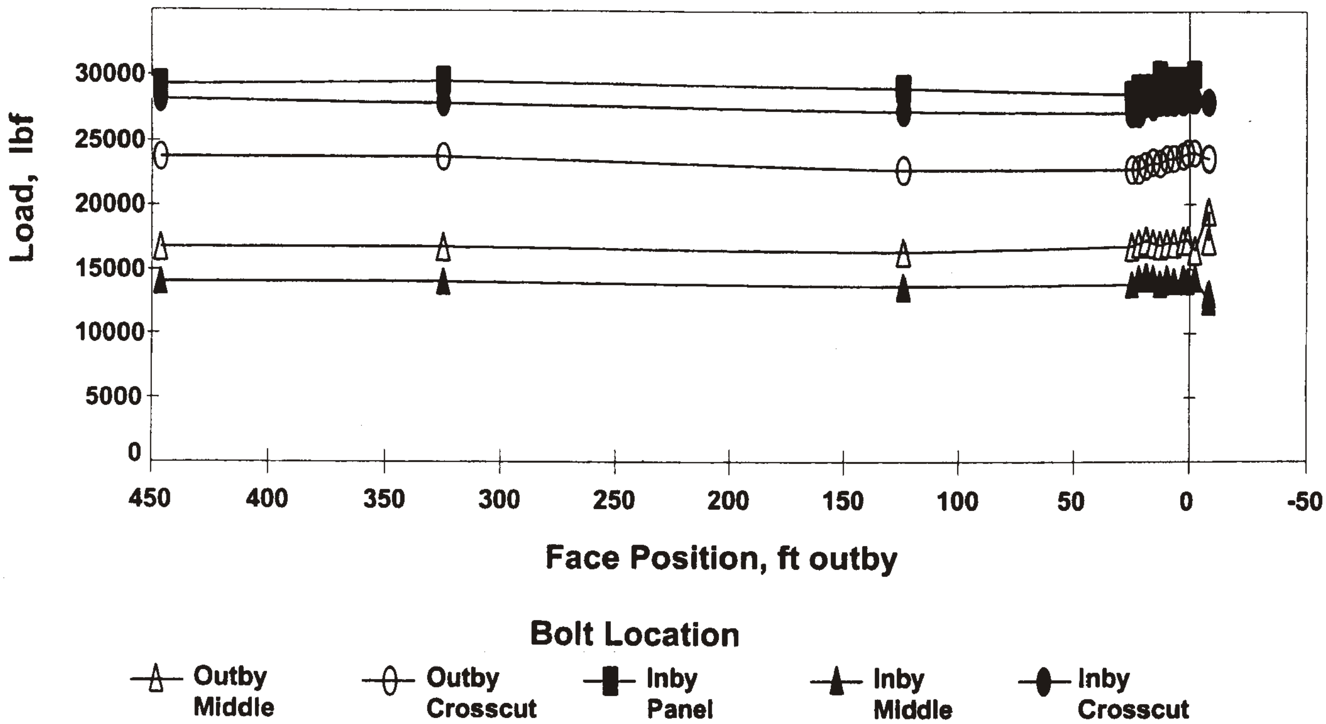

Figure A-9.—Bolt loads at mine E during the approach of the longwall.

MINE F

Mine F is a longwall mine located in Alabama's Black Warrior Basin at a depth of approximately 670 m (2,200 ft) [Signer et al. 1993]. Normally, the immediate roof is the Middleman, a fossiliferous shale that grades into thinly interbedded shale and coals. When the Middleman is the immediate roof, mining is said to be "single-seam." The Middleman is overlain by the 30-cm (1-ft) thick Mary Lee Seam. The main roof above the Mary Lee consists of 30 to 61 cm (1 to 2 ft) of competent siltstone overlain by massive sandstone. Horizontal stress caused roof guttering next to the future longwall panel in most of the test areas. A stress concentration was also carried with the tailgate corner during longwall mining.

The standard primary support in the tailgate was 19-mm (0.75-in) diameter, 1.8-m (6-ft) long, grade 40, nontensioned fully grouted bolts. The study compared these with 22-mm (7/8-in) diameter, 1.8-m (6-ft) long, grade 60, resin-assisted mechanically anchored bolts. Just prior to the headgate pass, an additional row of fully grouted resin bolts was installed between each row of primary supports.

Four study sites were chosen, two in areas supported by fully grouted bolts and two in areas supported by tensioned resin-assisted mechanical-anchor bolts. Two sites were located in intersections and two at midpillar. At each site, four instrumented roof bolts and three 3-point roof extensometers were installed (figure A-10).

The data shortly after development show that there was high localized loading in the fully grouted bolts and that several bolt locations had reached the yield point of the steel. Generally, the maximum load was measured by those gauges near the interface between the Mary Lee Seam and the main roof. At the midpillar site, greater bolt loads tended to develop on the bolts nearest the panel rib where the cutter formed. Bolt loads in the intersections were higher than those at the midpillar. The degree of loading on the tensioned bolts was similar to that on the fully grouted bolts.

Between development and the headgate pass the fully grouted bolts loaded up more rapidly than the point-anchor bolts. Several sections of the resin bolts passed into the strain-hardening phase of the plasticity curve (figure A-11). In the final days before the tailgate passed, loads increased significantly on nearly every bolt. Fifty percent of the strain-gauge stations on the resin bolts showed loads in excess of the yield point of the steel. The load increase on the tensioned bolts during the tailgate pass was very similar to that on the fully grouted bolts. However, the capacity of the point-anchor bolts was higher, and the loads remained below the yield point of the steel.

The roof deformation measurements showed that the greatest movements occurred along the panel rib, where the horizontal stress guttering was present. Greater roof movements also developed at the fully grouted bolt sites during the tailgate pass, and roof conditions were clearly more hazardous in the fully grouted bolt areas.

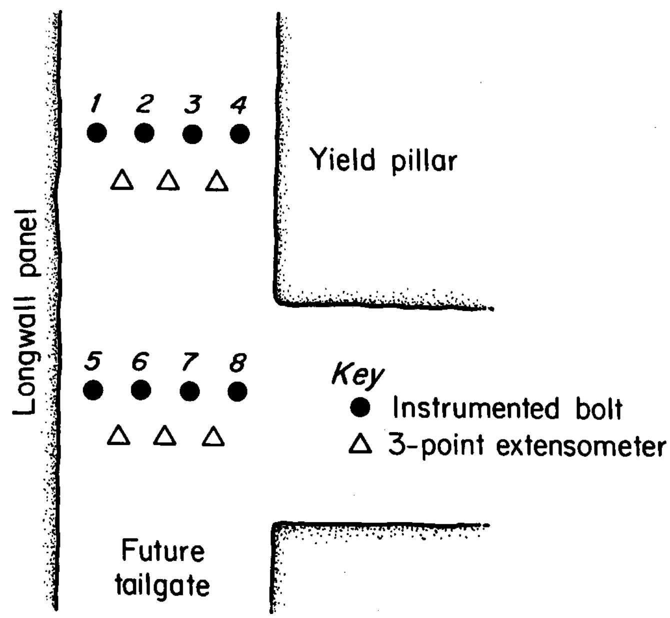

Figure A-10.—Study site at mine F.

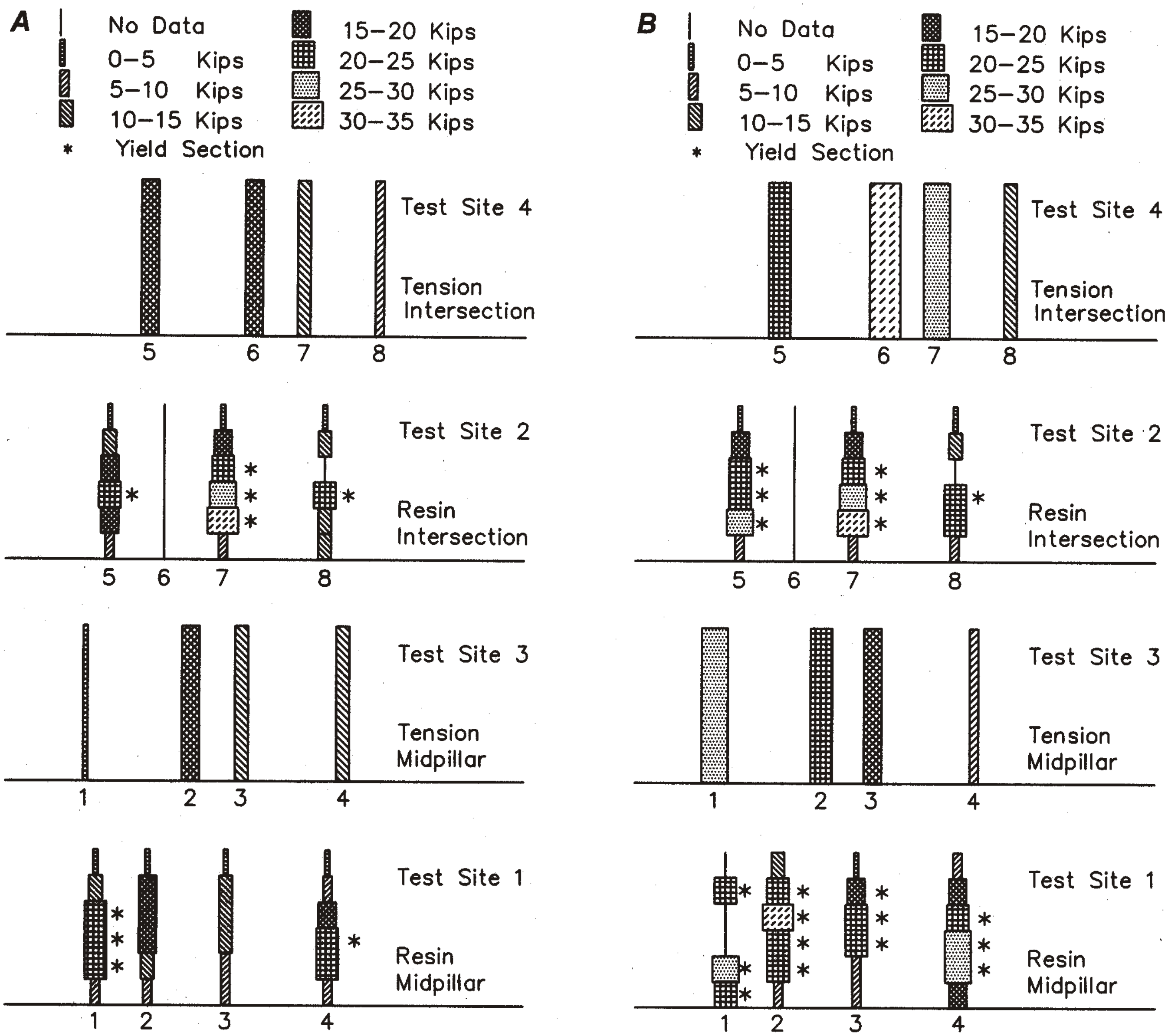

Figure A-11.—Bolt loads measured at mine F. The left-hand bolts are nearest the logwall panel rib. *A*, After the headgate pass; *B*, at the tailgate corner.

MINE G

Mine G employed continuous miner technology, including mobile roof support and continuous haulage, to retreat mine the Lower Kittanning Coalbed in central Pennsylvania [Campoli et al. 1996]. The depth of cover varied from 45 to 120 m (150 to 400 ft). The immediate roof was a sandy shale with a CMRR of about 50. Extensive stress mapping found local damage related to small geologic features (slickensides and fossiliferous bedding planes), but no significant correlation between direction of drivage and roof damage.

Borehole extensometers were installed in the roof of seven intersections, as shown in figure A-12. Two of the intersections (P2 and P4) were supported by 1.52-m (5-ft) resin-assisted point-anchor tension bolts. Three others (R2-A, R2-B, and R4) were supported by 1.83-m (6-ft) fully grouted resin bolts. The final two (R-P2 and R-P4) were supported by fully grouted bolts supplemented by two additional resin-assisted point-anchor bolts between each row. Hydraulic load cells were installed on four of the tensioned bolts at the P2 intersection.

The roof was monitored during both the developmental and retreat mining. Roof strains approaching 1% above the bolts were measured on development in one of the point-anchor sites (P-2 in figure A-13), but R-P4 was not far behind. These two intersections continued to see the greatest deformations as the pillar line approached, probably because of nearby "cutterlike" roof damage. Some appreciable roof deformations in the "skin" near the roof line were observed at a number of sites as the pillaring operations approached.

The bolt loading increased systematically from the No. 1 bolt to the No. 4 bolt. The No. 4 bolt, which was farthest from the coal pillar and near a "cutterlike" feature, saw a load of 100 kN (23,000 lb), which is near its yield point (figure A-14). The bolt loadings did not change significantly over time even when the pillars were recovered.

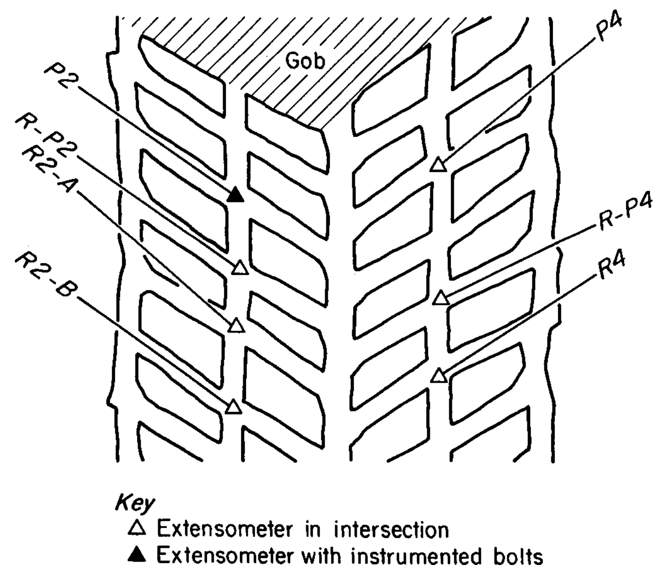

Figure A-12.—Study site at mine G.

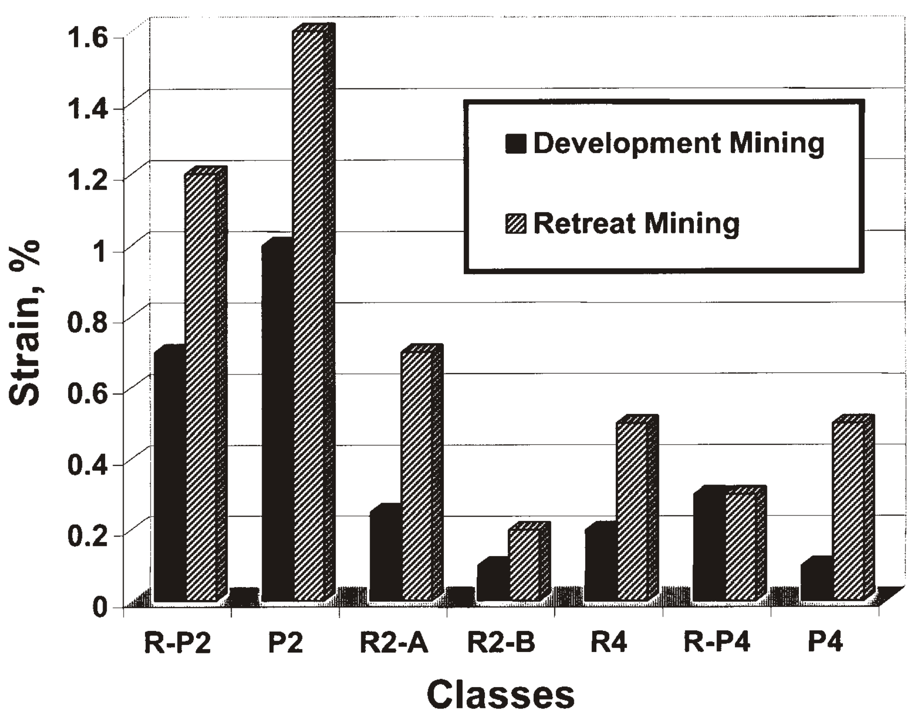

Figure A-13.–Maximum roof strains measured above the bolted horizon at mine G.

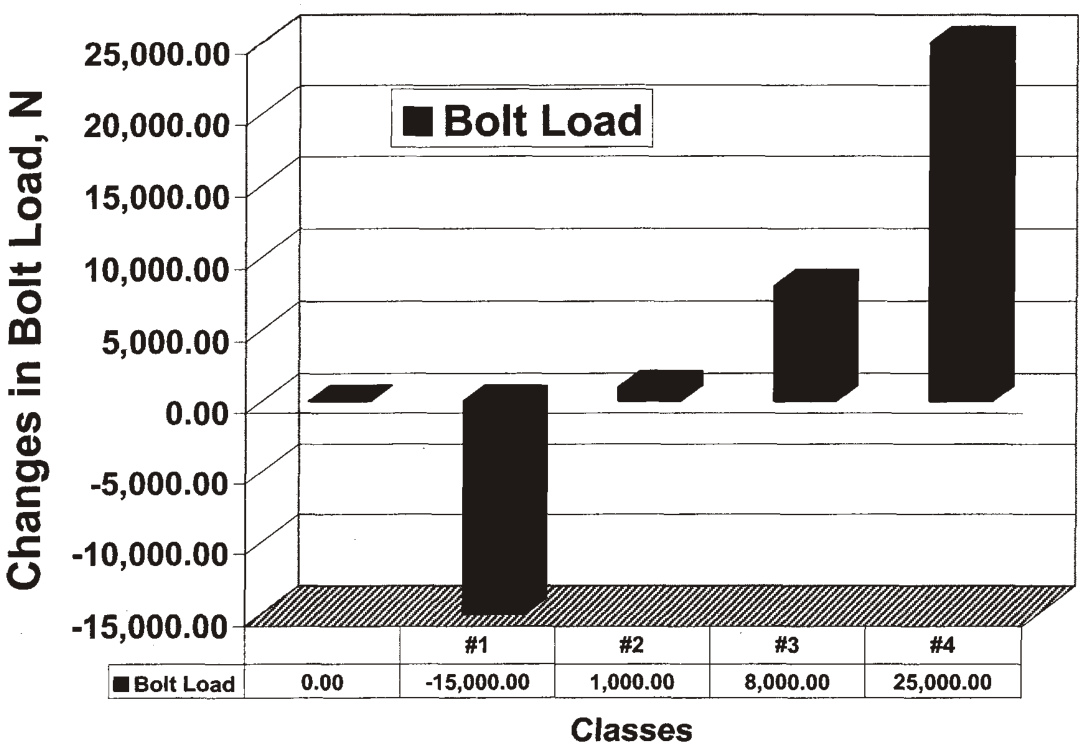

Figure A-14.—Changes in roof bolt loads measured at mine G. Bolt No. 4 is nearest a cutter; bolt No. 1 is nearest a solid rib.