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Statistical Evaluation and Time Series Analysis of Microseismicity, Mining, and Rock Bursts in a Hard-Rock Mine

By Jennifer Riefenberg

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

dB	decibel	Hz	hertz
ft	foot	in	inch
h	hour	kHz	kilohertz

STATISTICAL EVALUATION AND TIME SERIES ANALYSIS OF MICROSEISMICITY, MINING, AND ROCK BURSTS IN A HARD-ROCK MINE

By Jennifer Riefenberg[1]

ABSTRACT

The U.S. Bureau of Mines has long recognized the hazards associated with rock burst activity in underground mines. Concern over lost lives and resources prompted this study to further characterize rock burst occurrence as related to microseismicity and mining. A period of over 1,079 days of mining with 101 bursts, where microseismicity rates and blasting were recorded, was used in this study. Statistical analyses investigated relationships between (1) rock burst occurrence versus blasting, (2) rock burst size versus damage, (3) rock burst occurrence versus average microseismicity rates, and (4) rock burst occurrence versus local mine geometry. Statistical analyses showed that 91% of all rock bursts occur with blasting while only 3% of all rock bursts occur, apparently, independent of blasting. Additionally, the long-term average daily microseismicity rates appear to dictate when blasting will trigger rock bursts. Time series analysis on the daily microseismicity resulted in model equations that may be used to forecast the daily microseismic activity.

[1]Geophysical engineer, Denver Research Center, U.S. Bureau of Mines, Denver, CO.

INTRODUCTION

The detection, elimination, or control of rock bursts in underground mines throughout the world continues to be a major unsolved ground control problem even though the U.S. Bureau of Mines has been actively involved in microseismic rock burst research and monitoring for nearly 50 years (*31-34*).[2] Typically, rock bursts occur in mines at great depth (*30*), although geologic conditions affecting local stresses can create rock burst hazards at any mining depth (*15*).

Unexpected rock burst activity can result in the loss of lives and valuable mineral resources. Increasing the likelihood of successfully predicting a rock burst is an important task that is necessary to reduce injuries due to rock bursts. Quantifying the behavior of rock bursts and the relationships between microseismicity, mining, and rock bursts helps to increase the understanding of when a rock burst may occur. General methods of analysis that help to quantify rock burst characteristics are needed to accomplish this task. Statistical methods and times series analysis are logical approaches to evaluate the relationships between microseismicity, mining, and rock bursts.

For years, miners have developed a feel for a working area and have used this intuition to predict hazards. A thorough investigation of rock burst activity may quantify this miners' intuition. Two areas have been examined in this report: (1) characterizing microseismicity as a mathematical process, and (2) a statistical relationship between rock burst, blasting, geometry, and microseismicity (stress).

TECHNICAL APPROACH

The purpose of this study is to present a statistical analysis describing the occurrence of rock bursts in a deep hard-rock mine and to quantify relationships between microseismicity and mining, geometry, and stress. The study was conducted in two stages. The first stage investigated possible statistical interrelationships between microseismicity, mining, and rock bursts. The second stage of the study performed a time series analysis on the daily total microseismic events.

By analyzing microseismic data over a suitable timeframe, long-term cause-and-effect relationships may be delineated, and then, when thought necessary, short-term relationships may be investigated.

Although several studies using microseismic data have been documented, the majority of these analyses have been concerned with a period of a few days, hours, or minutes. Similarly, data used in these studies have typically covered only a single, or very few, bursts. The short-term studies investigating anomalous microseismic activity prior to failure have demonstrated some promising results, but there are still many failure occurrences for which no anomaly is observed. By statistically investigating many bursts over a long period, a clearer understanding of rock burst occurrence may be gained. For a fairly complete history of related studies, please refer to appendix A.

Microseismic data used in this study are from a deep, western U.S. silver-lead-zinc mine. The mining method used is cut-and-fill stoping and, at the time of this study, occurred at a depth of approximately 4,500 ft. The microseismic monitoring system consisted of eight to 12 accelerometers, with a frequency response of 20 Hz to 20 kHz, epoxied to the rock surface. The signal received at the accelerometer was then preamplified at +40 dB, enabling the signal to traverse the length of cable to the recording equipment. The signal was again amplified at the recording site and transmitted to the rock burst monitor (RBM) to validate the signals. The RBM is a threshold exceedance device, which captures the time of first arrival of the microseismic event for each accelerometer. In addition, the RBM only accepts events in which five or more accelerometers were activated with a detectable first arrival. Figure 1 depicts a schematic diagram of the microseismic monitoring system.

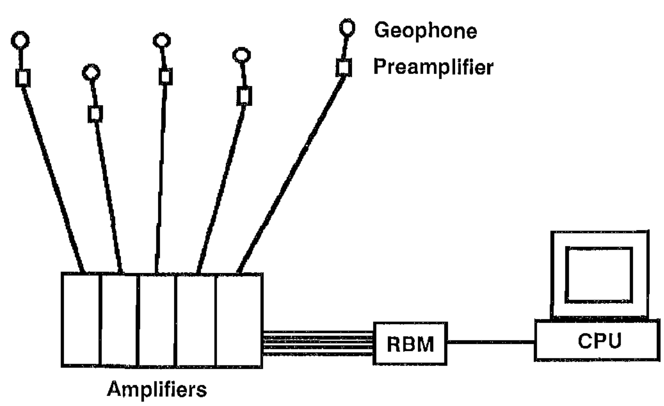

Figure 1.—Generalized schematic diagram of microseismic monitoring system used in this analysis. Diagram shows geophones, preamplifiers, amplifiers, rock burst monitor (RBM), and computer which collects and processes the data (CPU).

[2]Italic numbers in parentheses refer to items in the list of references preceding the appendixes at the end of this report.

These microseismic events, which have been validated by the RBM, are then sent to a computer that records the arrival time information and computes a source location for the event. Of those events which are locatable, two types of records are catalogued: (1) the complete arrival time record, which includes arrival times to each accelerometer, source location of the event, and time of microseismic event (time of first arrival), and (2) the partial record which includes only the number of microseismic events that occurred in one day. It is only the latter information, namely the number of daily microseismic events, which were available for this study. In addition, the mine, in cooperation with the Bureau's Spokane Research Center, maintains a surface seismograph on which larger size bursts and earthquakes are recorded.

Five microseismic data sets, ranging over a period from mid-1984 through late-1987, are used in this analysis. A data set is defined as microseismic data collected in a single stope and occurring over a period that has no gap longer than about one week in the record. (Small gaps that appear in the data sets are filled in by replacing the missing data with an average from the surrounding days' events.) Included in these data sets are the daily total of (locatable) microseismic events and the daily mining activity. The suite of data is from three stopes in the study mine. The shortest period is 73 days, and the longest period is 315 days. The complete data suite contains 1,079 days with 101 total rock bursts and bumps. Refer to table 1 for a summary of these data.

At the mine, the word burst is used to mean a large failure, or one for which the seismograph located at the surface records at least 1-in amplitude, and a bump means a small burst, or one which records less than 1-in amplitude on the surface seismograph. Though the surface seismograph amplitude provides an inexact estimate of the energy associated with failure, this provides an estimate for mine personnel. In this report, the term burst will be used to represent both a burst and a bump. Most microseismic events are not large enough to trigger the surface seismograph and, thus, those events that are capable of triggering the surface seismograph are considered to be bursts. Additionally, no distinction is made between production blasting and destress blasting. Because the field records do not always distinguish between a production- and a destress-blast, separating the two was not possible.

Table 1.—Summary of microseismic event data

Data set	Time period	Stope	Total number of— Days	Bursts	Blasts	Average number of events
1	10/1/84-12/12/84	A	73	20	21	125.0 (139.5)[1]
2	1/2/85-6/30/85	A	180	45	49	229.6 (151.0)
3	1/1/86-6/30/86	B	212	11	28	213.4 (155.8)
4	10/1/86-8/12/87	B	315	8	49	95.1 (122.6)
5	3/6/87-12/29/87	C	299	17	101	113.7 (134.4)
Total or average			1,079	101	248	148.3[2]

[1]Sample standard deviation.

[2]Average for 5 data sets. The average for 1,079 days of events (n = 1,079) = 155.4.

STATISTICAL EVALUATION

EXAMINATION OF RELATIONSHIP BETWEEN ROCK BURSTS AND BLASTING

Nearly all of the 101 recorded bursts occur with blasting (figs. 2-6). Specifically, 91% of all bursts occur within a 12-h window after blasting, and, of these events, 95% occur immediately with blasting. Seventy-eight percent of the bursts, which do not occur in the 12-h postblast interval, do occur between 12 and 48 h after blasting. Only three events (<3%) occur outside of the 48-h postblast interval.

Bursts, which occur outside of the 12-h interval, may be related to blasting in adjacent areas, or may be triggered by a burst sequence occurring nearby. Events that occur within the 48-h interval often occur within 24 h following a separate burst. Inferring that any burst occurs independent of some trigger-type mechanism is premature. Blasting sequences in adjacent areas are often unavailable, and as has been observed, blasting in a nearby zone can trigger a burst outside of that zone. For example, on February 22, 1985, mine personnel reported that the blast in stope A apparently triggered a burst in an adjacent stope as well as triggering a burst in stope A.

Recall that, at the mine, any seismic event that is recorded on the surface seismograph is termed a burst (or bump). Using this definition, very few bursts result in visible damage (8%). This result, as of yet, is inconclusive and maybe misleading in that, if the damage due to the burst occurs in the same vicinity as the blast, failure may be indiscernible from damage due to the blast itself. As observed by Cook (*10*), only a small fraction of seismic events cause damage and, additionally, the percentage of rock bursts rises with increasing magnitude of events. In a study by McLaughlin (*27*), a ratio of damaging bursts to all bursts was determined to be approximately from 0.1 to 0.3.

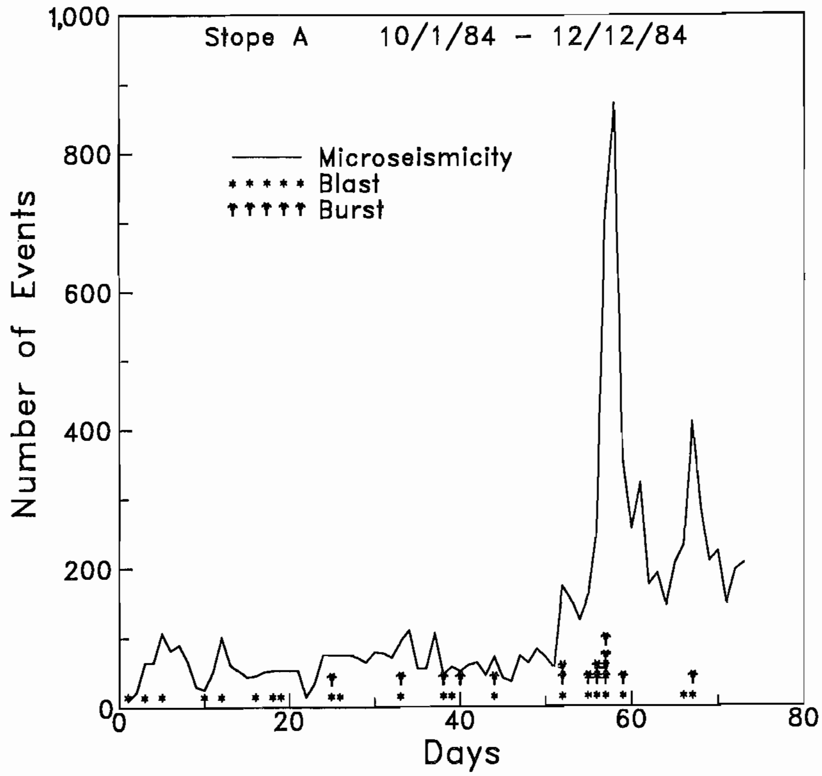

Figure 2.—Daily microseismicity for stope A, 10/1/84-12/12/84. Times of blasting and rock bursts are also plotted.

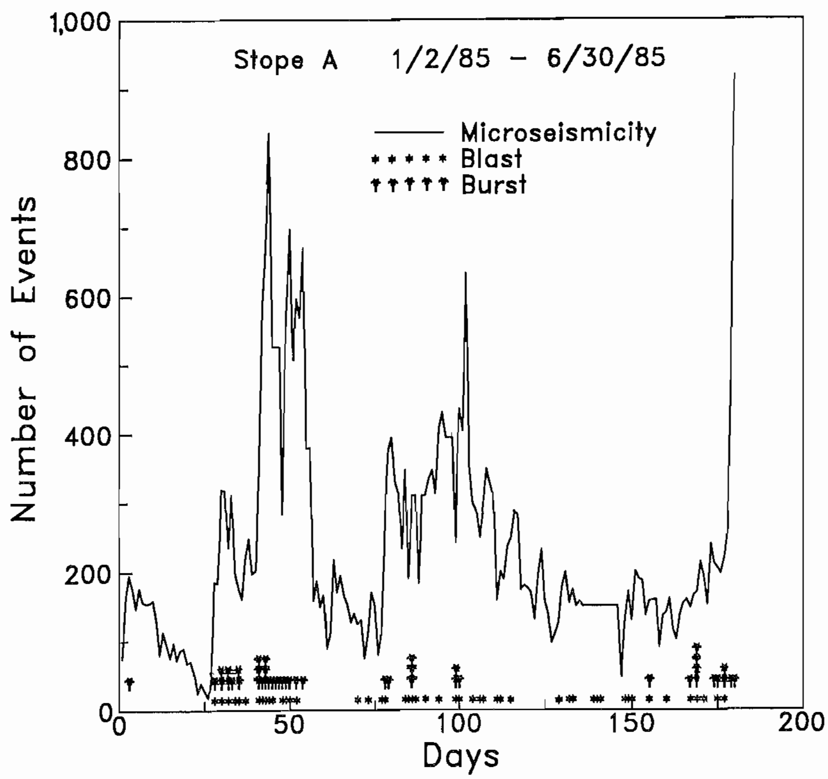

Figure 3.—Daily microseismicity for stope A, 1/2/85-6/30/85. Times of blasting and rock bursts are also plotted.

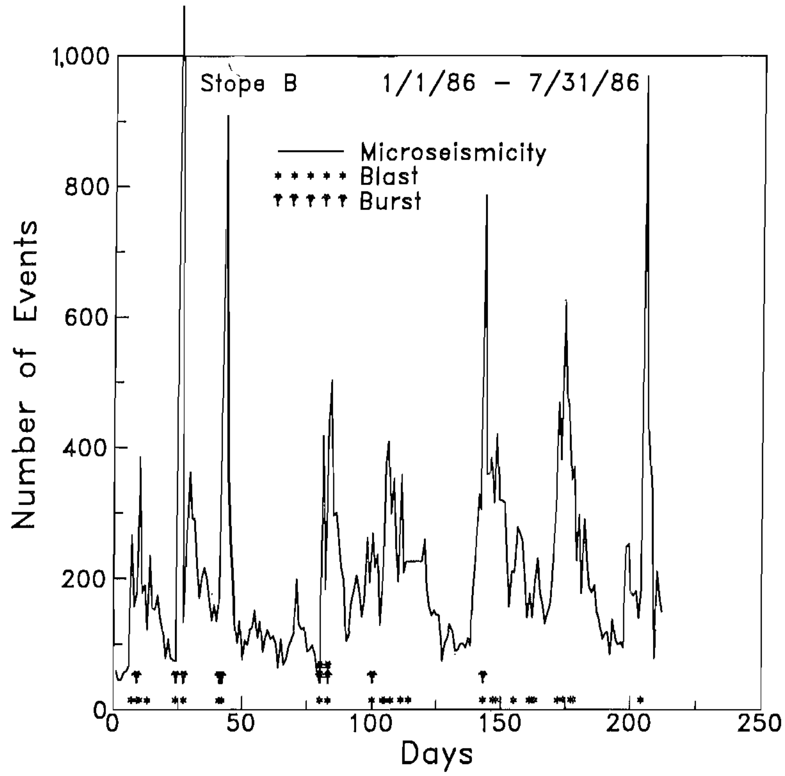

Figure 4.—Daily microseismicity for stope B, 1/1/86-7/31/86. Times of blasting and rock bursts are also plotted.

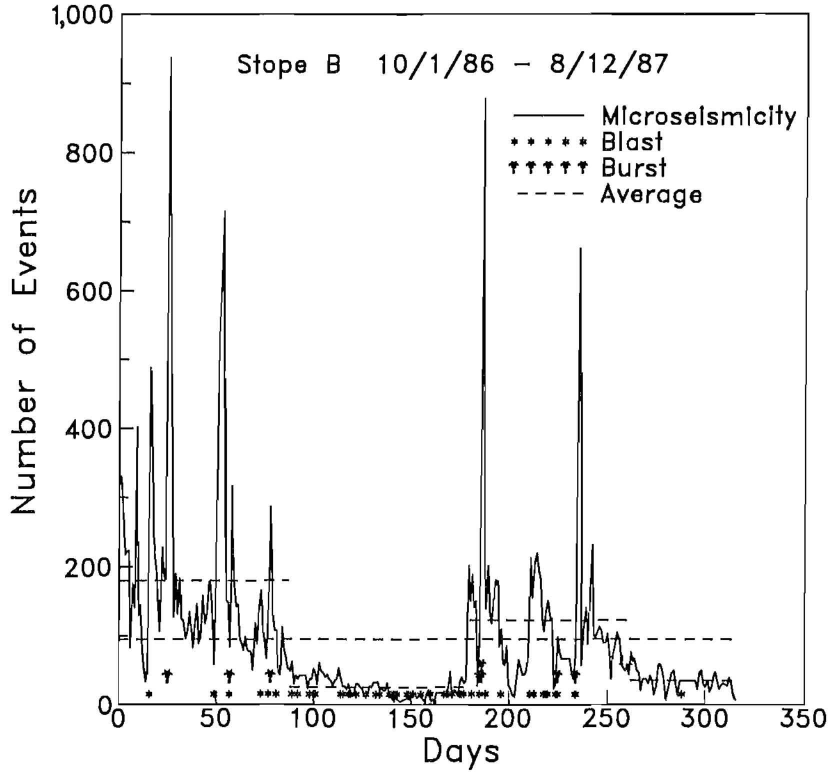

Figure 5.—Daily microseismicity for stope B, 10/1/86-8/12/87. Times of blasting and rock bursts are also plotted. Average microseismicity for indicated time periods are also included on plot.

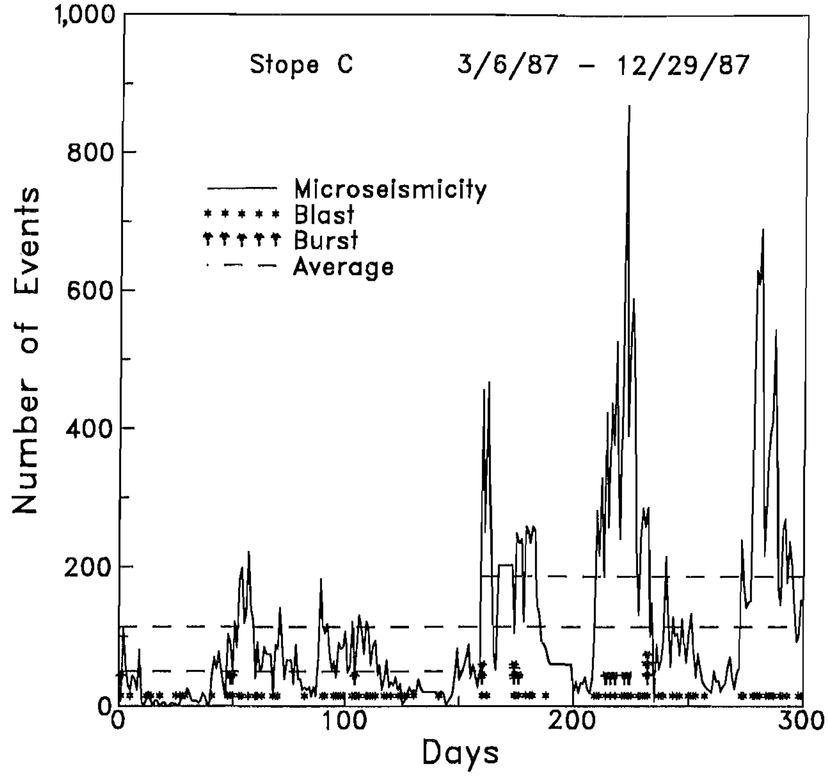

Figure 6.—Daily microseismicity for stope C, 3/6/87-12/29/87. Times of blasting and rock bursts are also plotted. Average microseismicity for indicated time periods are also included on plot.

EXAMINATION OF ROCK BURST SIZE VERSUS DAMAGE

Magnitudes based on a surface seismograph signal amplitude appear to be of questionable accuracy. Collecting accurate magnitude measurements is necessary prior to stating any strong conclusions on resultant damage versus size. Observations made by Lenhardt (*23*) are, "Not all seismic events cause damage to underground excavations. A recent study (Lenhardt, 1988a) revealed that 50% of all seismic events M>1,8[3] on the carbon leader reef (CLR) result in rockbursts. ... Obviously, the higher the magnitude - the higher the chance of damage and loss of production."

In all but one occurrence of damage reported in this study, the associated bursts were of small amplitude (<< 1.0-in). In the three bursts, which occurred independent of known blasting, the amplitude 3.38-in event caused no visible damage, the amplitude 2.08-in event resulted in minor damage to the stope, and the amplitude 0.2-in event resulted in no damage. There is insufficient evidence in this data to determine a relationship between rock burst size and damage. Of interest though, Gay (*12*) determined a relationship between rock burst magnitude and blasting and found that blasting generated smaller events whereas the large magnitude events occur, apparently, independent of blasting.

On occasion, a failure occurs without a detectable event to account for it. For example, on January 17, 1985, in stope A, damage was reported, yet no bump or burst was detected. Similarly, on February 14, 1985, a rib slab fell near stope A, resulting in minor damage, yet no burst was detected. Failures of this type are probably due to weakening that occurred at some earlier time and failed only as time and gravitational force acted upon the weakened area. Failure may also be due to geologic anomalies.

EXAMINATION OF RELATIONSHIP BETWEEN ROCK BURSTS AND AVERAGE MICROSEISMICITY RATE

In situ stress data are not available in this study, yet it has been demonstrated that the average level of microseismic activity is higher when load is applied (*8, 11, 18, 24-25, 29-30, 34, 38, 41*). It is reasonable to assume that the major cause of rock burst activity is stress and, therefore, correlation between stress and rock bursts may be approximated using average microseismicity rates.

Figures 5 and 6 show two data sets that provide a sufficiently long interval to observe this effect: rock burst

[3]Seismological term where M is a measure of magnitude.

activity increases when the average daily event count is high. In figure 5, the average for the entire data set is 95.1 counts-per-day. In the first 3-month period (87 days), the average count per day is 180.4—nearly double the overall average. It is also in this interval that rock burst activity is prevalent. In the second 3-month period (92 days), rock burst activity is nonexistent and the average counts-per-day is only 25.0, or 3.8 times less than the overall average. In the third 3-month period (82 days), which is again burst active, the average counts-per-day is 122.5. In the final period (55 days), an interval that is seismically quiet, the average is 35.1. In the second example, figure 6, the overall average for the complete data set is 113.7 events per day. In the first five-plus months (158 days), the average counts-per-day is 50.1 or less than half the overall average. This first period is seismically quiet, whereas, the second 5-month period (141 days), being seismically active, has an average counts-per-day of 185.8—substantially higher than the overall average.

EXAMINATION OF RELATIONSHIP BETWEEN ROCK BURSTS AND LOCAL MINE GEOMETRY

Some spatial clustering of rock burst activity is present (fig. 7); rock bursts do not appear to occur randomly in a spatial sense. In this figure, the location of the event is not with respect to computed spatial coordinates, but that, the location is with respect to time. Thus, the location of the events are where active mining was taking place when a burst occurred. For example, in stope A activity increases when mining near and into a nearby I-drift and when mining to the west side of the raise. Stope B indicates two possible zones where burst activity increases: near to and far from the raise. In stope C, microseismic activity appears to occur when mining nears the raise.

Recall that the data set consisted only of the partial records containing the number of locatable events that occurred on each day. Because of this, actual computed source locations for these rock bursts are unavailable and without locations, statistical cluster analyses cannot be used to quantify the geometric nonrandomness of the events.

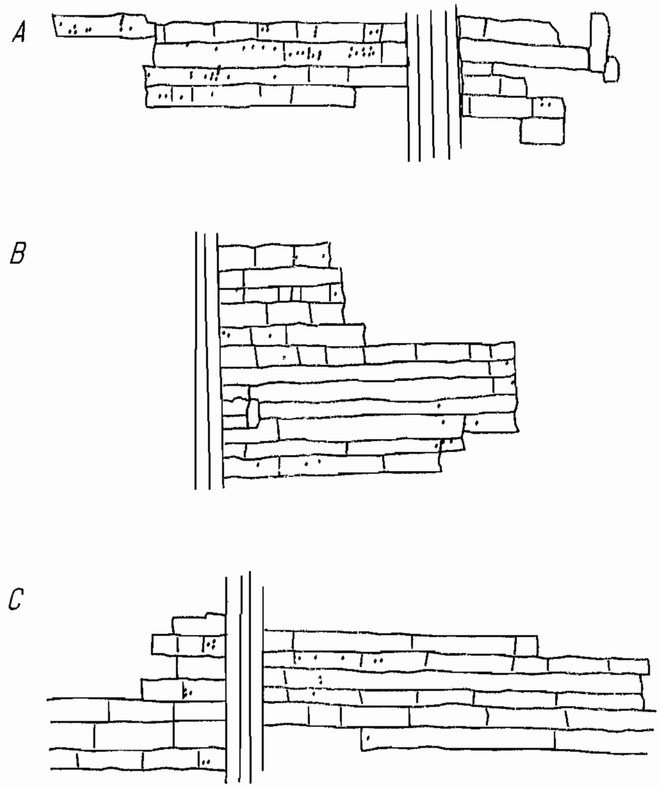

Figure 7.—Cross-sectional view of (a) stope A, (b) stope B, and (c) stope C with rock bursts plotted as occurring with respect to time. Mining and time progress upward.

Though stress-state information is unavailable, the areas showing rock burst activity are most likely areas of high local stress. Further analysis and more detailed information on the mine geometry as well as local geologic features, rock burst source locations, and stress conditions are warranted. In 1988, Scott (*37*) reported on relationships between geology and rock burst and concluded that rock bursts were highly dependent on geology, and in particular, on the hardness of the surrounding rock mass. Similar laboratory and theoretical work by Salamon (*35-36*) relates the stiffness of the loading mechanism as a driving force in catastrophic failure.

TIME SERIES ANALYSIS—APPROACH

The second stage of this study is to perform a time series analysis on the daily total of microseismic events. Stationary, linear time series techniques may delineate periodic or other mathematically definable trends that are present in the data. In 1988, Bath (*4*) found no pronounced periodicities in the time history of microseismic data, yet these studies did not utilize advanced mathematical techniques such as time series analysis. Bath did find rough correlation with respect to rainfall, etc., and microseismicity. In general, one may assume (as is often the case) that data are a function of themselves, past data, and white (random) noise. Time series analysis is a method of quantifying data as the superposition of various definable mathematical processes and random noise. The approach is to remove, one-by-one, each mathematical process, defining each as it is removed, until all that remains of the data is the white noise component. General trends such as linear or nonlinear behavior and periodic cycles are defined and subtracted from the data first, and then, what are termed ARMA processes may be delineated and removed. Linear and nonlinear trends are defined in the data through regression analyses, results of which are then subtracted from the data set. Similarly, cyclical features are removed through methods such as differencing the time series. ARMA processes are autoregressive (AR) processes coupled with moving average (MA) processes. AR processes are the portion of data that are a function of themselves. AR(p) terminology refers to the p time steps of which the data are a function. Similarly, the MA processes are the portion of the data which are a function of white noise. MA(q) terminology denotes the q time steps of white noise that the data are a function of. Thus, ARMA, or ARMA(p,q), processes are the underlying mathematical processes which describe the data.

In this study, the time series analysis was on the daily total microseismic events and, thus, the time step is one day. The daily total of locatable microseismic events for each data set is plotted (figs. 2-6) and the sample means and variances computed (table 1). Log-transforming time series data is a common transformation used in time series analysis as many data sets contain large amplitude changes with time. These log-transformations may also be part of the superposition of mathematical functions of which the data consists.

By reviewing the sample autocorrelation function (ACF) and sample partial-autocorrelation function (PACF) the presence, and order (values of p and q), of ARMA(p,q) processes can be determined. By observing the sample ACF and PACF, and comparing them to the theoretical ACF and PACF of the class of ARMA(p,q) models, one may select a collection of appropriate ARMA models to fit the data set. Various order ARMA processes, which makeup the selected collection, based on the sample ACF and PACF's, are then tested to determine a single best process (based on the Akaike (*1-3*) information criterion (AIC), Bayesian information criterion (BIC), and final prediction error (FPE) statistics). The resulting ARMA process is used to compute preliminary parameter estimates of the coefficients in the ARMA model. Once preliminary estimates have been determined, optimization of the coefficients result in an ARMA model equation. Analyses on the data residuals test the validity of the ARMA model. For a complete discussion and mathematical basis for this time series analytic method, the reader is referred to Brockwell and Davis (*8*).

To briefly demonstrate, general ARMA(p,q) models are written as

$$X_t + c_1X_{t-1} + c_2X_{t-2} + \dots + c_pX_{t-p} = Z_t + a_1Z_{t-1} + a_2Z_{t-2} + \dots + a_qZ_{t-q} \qquad (1)$$

where, X_t is an event occurring at time, t, p is the order of the autoregressive process, Z_t, $t = \{0, +/-1, +/-2, \dots\}$, is a sequence of independent, identically distributed normal, $N(0, \sigma^2 < \infty)$ random variables, and q is the order of the moving average process. Additionally, a and c are coefficients for the ARMA model equation. Thus, an example ARMA(1,2) process is of the form:

$$X_t = Z_t + (0.65)Z_{t-1} + (-0.43)Z_{t-2} + (0.8)X_{t-1}. \qquad (2)$$

Once an appropriate ARMA process has been determined, forecasts on the data may be made using this ARMA equation. Time series forecasts are based on long-term trends, periodicities, the sample mean, and the ARMA model equation. Forecasts made using time series methods are expressed within confidence intervals. Appropriateness or viability of these forecasts will depend on the data and on what the data are intended to demonstrate.

TIME SERIES ANALYSIS—RESULTS

Referring to figures 2-6, no periodicities nor long-term trends appear in the data. Owing to the highly skewed nature of the data, each data set was log-transformed prior to delineating ARMA processes. All that is necessary to remove from the then log-transformed data is the sample mean. The next step in the time series analysis process is to delineate ARMA processes occurring in the data. Appendix B contains graphs of the ACF's and PACF's for the five data sets used in this analysis. Investigation of the PACF's indicate the presence of AR processes of order less-than or equal-to eight (AR(8)). Likewise, MA processes of order less than or equal to two (MA(2)) may be indicated.

Numerous ARMA models were tested, and a reasonable model selected and defined for each data set. Table 2 contains a summary of these selected ARMA models. Appendix B also contains a table of resulting statistics used in selecting appropriate models. In all cases, there is an AR process of at least order one present (AR(1)); thus, the data at time t depends on data at the previous time step.

Table 2.—Resulting ARMA models for five data sets

Data set	General model	Model equation[1]
1	AR(1)	$Y_t = Z_t + 0.865Y_{t-1}$.
2	AR(1)	$Y_t = Z_t + 0.863Y_{t-1}$.
3	AR(1)	$Y_t = Z_t + 0.686Y_{t-1}$.
4	AR(6)	$Y_t = Z_t + 0.64Y_{t-1} + 0.107Y_{t-3} + 0.188Y_{t-6}$.
5	AR(8)	$Y_t = Z_t + 0.633Y_{t-1} + 0.142Y_{t-3} + 0.095Y_{t-4} + 0.165Y_{t-7} - 0.129Y_{t-8}$.

[1] $Y_t = \ln X_t - \overline{\ln X}$.

Forecasts of the time series data will predict the expected daily microseismicity based on the ARMA model, the sample mean, and the retransformation of the logged data. A powerful feature of this time series technique is that the forecasts can be made with user-defined confidence. Appendix B contains 5-day forecasts, at the 95% confidence level, for each data set based on the ARMA model derived for each set. Even though microseismicity forecasts do not provide a basis for prediction of rock bursts, it is an important result that daily microseismicity is not random, and that it is a function of prior activity.

In summary, there are two main points to be concluded from this analysis. First, even though mining occurs in cycles, the cycles are not perfectly periodic, and, therefore, time series analyses will not recognize these cycles. Perhaps nonlinear and/or nonstationary time series methods can be used to delineate aperiodic cycles. Second, there is sufficient evidence to demonstrate that microseismic activity is not a purely random process. Microseismic activity occurring on any given day does affect the microseismicity on future days. Perhaps time series analyses using smaller intervals, such as minutes or hours, will reveal important characteristics of microseismicity. Fractal and chaotic distributions of microseismicity in time and space may also be considered for further investigation in the characterization of microseismicity.

SUMMARY

- Ninety one percent of all rock bursts occur with blasting.
- Less than 3% of all rock bursts occur, apparently, independent to blasting, although blasting in adjacent areas is unavailable to confirm this result.
- The average daily level for microseismic activity may provide a long-term indicator of rock burst hazard by delineating areas of high stress.
- Local geometry and geology appear to affect rock burst activity as indicated by the apparent clustering of bursts.
- Time series analysis revealed nonrandomness in microseismic event rate data. Strong correlation was determined to exist between daily events.

CONCLUSIONS

The analyses undertaken in this report provide information on cause-and-effect relationships between mining, microseismicity, and rock burst activity. First, what has been experienced in the mine has been numerically quantified and confirmed. Thus, this study has numerically supported miners' intuition and their feel of an area. This includes the relationships between rock bursts and blasts (unusual), or an increase in the average (normal), microseismic activity versus rock burst, and mine geometry related to rock bursts.

Second, future directions of investigative research may be better prioritized based on the results presented herein. For example, since it has been shown that there is a high correlation of burst activity with blasting, postblast sequences may be an important area of study. Implementing a stress analysis program, with the microseismic monitoring, appears to be an essential component to assure any success in understanding rock burst occurrence. In addition, it may be determined what type of data is important to record. For example, this analysis has indicated that mining cycles and local stress conditions should be collected in addition to microseismic activity. Fairly detailed geologic and geometric conditions in the local mine area need to be recorded and correlative analyses with rock burst activity investigated.

By analyzing long-term average microseismic-event rates, a change in average activity may indicate a change in rock burst occurrence. When activity is low, there appears to be little need for detailed microseismic or stress analyses. Only when an increase in average activity occurs may a detailed investigation be warranted. Destressing an area when there is little or no danger of rock burst occurrence can be a costly process. Costs may be reduced by taking preventive measures only when potential failure is likely.

Questions to be asked in a rock burst prevention process may be: Has average microseismic activity increased? Have geologic conditions or mining geometry changed to warrant high stress concerns? Has rock burst activity been experienced in the same area at past cycles in time? If the above conditions appear to indicate potential problems, then investigate the area in detail. Detailed, full-waveform microseismic analyses, stress measurement analyses and, other analyses can be undertaken to further characterize the area of concern.

The general statistical approach for analyzing, or characterizing, rock burst activity can be used effectively in any type of mine. By systematically investigating mining areas, from the general to the particular, an increase in the likelihood of detecting potential hazard areas exists.

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APPENDIX A.—HISTORY

Mining areas in the United States and throughout the world have experienced rock burst problems, especially as depths of mining have increased. Many studies have attempted to characterize and predict rock bursts using microseismics. As early as 1941, Obert and Duvall (*33*)[1] reported on using subaudible noise, or microseismicity, as a precursor for rock bursts. In 1942, Obert and Duvall (*34*) continued with the initial study by investigating microseismicity in a hard-rock mine. This study led to the development of a predictive model based on an anomalous increase in microseismic activity prior to failure. This early work and subsequent laboratory work by Obert and Duvall (*31-32*) have influenced and guided many studies even to date.

In 1975, Trombik and Zuberek (*41*) noted an increase followed by a decrease in microseismic activity preceding failure in many of the rock bursts occurring in a coal mine. Similarly, in 1978, McKavanagh and Enever (*26*) investigated microseismicity in a coal mine, and when active mining had ceased, noted an anomalous increase in activity followed by a decrease in activity preceding failure in three of five cases studied. Also in 1978, Brady (*7*) investigated microseismicity associated with a rock burst in a hard-rock mine and a roof fall in a coal mine. In this work, Brady presented a deterministic prediction theory in which he states: "... the seismicity anomaly (seismicity increase followed by a decrease prior to failure) is a necessary condition for failure."

While many studies have demonstrated short-term precursory effects, other studies have been unable to show this condition for failure—an increase and subsequent decrease in microseismic activity. For example, Chugh and Heidinger (*11*) performed unconfined compression tests on coal samples in which they investigated microseismicity related to the coal lithology. They observed an increase in microseismicity as stress increased, yet "Reduced microseismic activity just prior to failure ... was not observed during the experiments." Similarly, Leighton (*21*) cites cases from a coal mine study where no anomaly in the event rate occurred prior to failure, as well as cases where an anomalous sequence occurred, yet no failure followed. In 1988, Johnston and Einstein (*15*) concluded that acoustic emission[2] rates were not a reliable method for prediction based on precursory anomalous behavior.

In 1975, Leighton and Steblay (*22*) investigated a coal mine and noted spatial clustering as well as increased activity in the microseismicity preceding failure. In 1978, Trombik and Zuberek (*40*) investigated spatial clustering of microseismic events through time as mining progressed in a coal mine. They observed clustering of the microseismic activity ahead of the face and where load was presumed to be at a peak. Similarly, Leighton (*20-21*), studied both a hard-rock mine and a coal mine using spatial clustering and event count rates. Kneisley (*19*) investigated a coal mine and found anomalous increases in microseismicity prior to failure in addition to spatial clustering of events. Kneisley noted that failure tended to occur away from the location of the clustering of events. In 1984, Marcak (*24*) reported on a coal mine study investigating seismoacoustic response to mining-induced stress and noted a time dependence in the seismicity. Calder, Archibald, Madsen, and Bullock (*9*) studied a blast induced rock burst and found a correlation between peak event rate and pillar stress. Similarly, McWilliams, McDonald, and Jenkins (*28*) characterized microseismic activity rates as related to pillar size.

Microseismicity studies led Blake (*6*) to investigate destressing based on a microseismically active area as a preventive measure regarding failure with promising results. Uniaxial compressive tests on coal were studied in the laboratory by Chugh and Heidinger (*11*), and McCabe (*25*). These researchers, as have many others, found a general increase in the number of microseismic events due to increased load. Khair (*17*) investigated microseismicity in laboratory tests on granite and coal using varied loading conditions and, again, detected increased microseismic activity with increased load. Khair also noticed fluctuations in the microseismicity and stated: "Each low point on the stress-strain curve is indicative of local failure and stress relaxation in the specimen....In general the peak in the A.E. [acoustic emission] pattern indicates the frequency of crack closure, initiation and propagation in the material." Khair and Hardy (*18*) performed laboratory tests in which coal samples were pressurized with various gas types simulating outburst conditions and acoustic emissions monitored. They found an increase in microseismicity as the specimens were being pressurized. Sondergeld and Estey (*38*) demonstrated that microseismic activity increases with increased loading in a laboratory study of Westerly granite deformed in a uniaxial cycling experiment. This is only a partial listing of the many researchers undertaking laboratory testing of rock samples related to microseismicity and/or acoustic emission rates.

More recent studies include laboratory uniaxial and triaxial tests on various rock types by Michihiro, Hata, Fujiwara, Yoshioka, and Tanimoto (*29*) investigating count rates versus load and m-values for predicting rock bursts.

[1]Italic numbers in parentheses refer to items in the list of references preceding the appendix.

[2]At times in this report, the term acoustic emission is referenced. This report will not distinguish between an acoustic emission and a microseismic event. These terms are often used interchangeably in the literature and in the field.

Another area of recent research is in the characterization of microseismic-event waveforms, and/or failure mechanisms, in the hopes of delineating failure-prone areas see, for example, studies by Swanson and Boler (*39*), and Billington, Boler, Swanson, and Estey (*5*).

Owing to the complexity of the problem, researchers have recognized that microseismicity alone does not provide enough information to make strong predictions concerning rock burst occurrence. "... microseismic information must be coupled with experience or stress-gage information, for, by itself, it offers only an indication." [Leighton (*21*)].

Research, using microseismic techniques to characterize and predict rock burst occurrence, has led to the development of some useful techniques in recognizing and reducing hazards associated with high stress conditions. For example, short-term temporal and/or spatial anomalies in microseismicity prior to failure have been used, with limited success, to predict rock bursts. Correlation between load and average-levels in microseismic activity may also be an effective tool in recognizing hazard.

In 1975, Trombik and Zuberek (*41*) made predictions on rock bursts in a coal mine based on blasting and anomalies in microseismicity rates. Out of 18 total bursts, 11 were correctly predicted to occur simultaneously with blasting, five were correctly predicted based on anomalies, and two bursts were unexpected. These researchers demonstrated that most of the bursts which occurred, did so as a result of blasting. Similarly, Watanabe, Nakajima, and Itakura (*42*) discussed prediction of rock burst based on blasting and postblast microseismicity. Lenhardt (*23*) states: "... at least 40% of all seismic events occur outside blasting time, although they are spread over a period of 20 h. ... Only in the magnitude range $M>3$ do we find a little dominance outside blasting time,... The link between production blasting and mining induced seismicity is obvious ... During blasting time the mine experiences a more than tenfold increase in the frequency of seismic events ($M>0$)." In 1988, McWilliams, McDonald, and Jenkins (*28*) determined a roughly linear relationship between the number of microseismic events and mine-wide blasting.

Hill (*13-14*), in the early years of rock burst research, examined the influence of layout, shape of abutment, and geological weaknesses on rock bursts. Will (*43*) presented a coal mine field study that compared microseismicity rates to various mining operations. Similarly, Nakajima and Watanabe (*30*) studied relationships between advance boring and acoustic emission activity in a coal mine. Both of these studies demonstrated a general correlation between microseismicity and mining activity. Kaneko, Sugawara, and Obara (*16*) stated that the energy release density (microseismic energy per unit area) is a precursor of coal bursts.

APPENDIX B.—STATISTICS AND FORECASTS

The following appendix contains information for the time series analysis portion of the report. Included in this are the ACF and PACF plots for each (log-transformed) data set, a table of statistics from which the models were selected, and a listing of the forecasts for each data set where the forecasts are at the 95% confidence level.

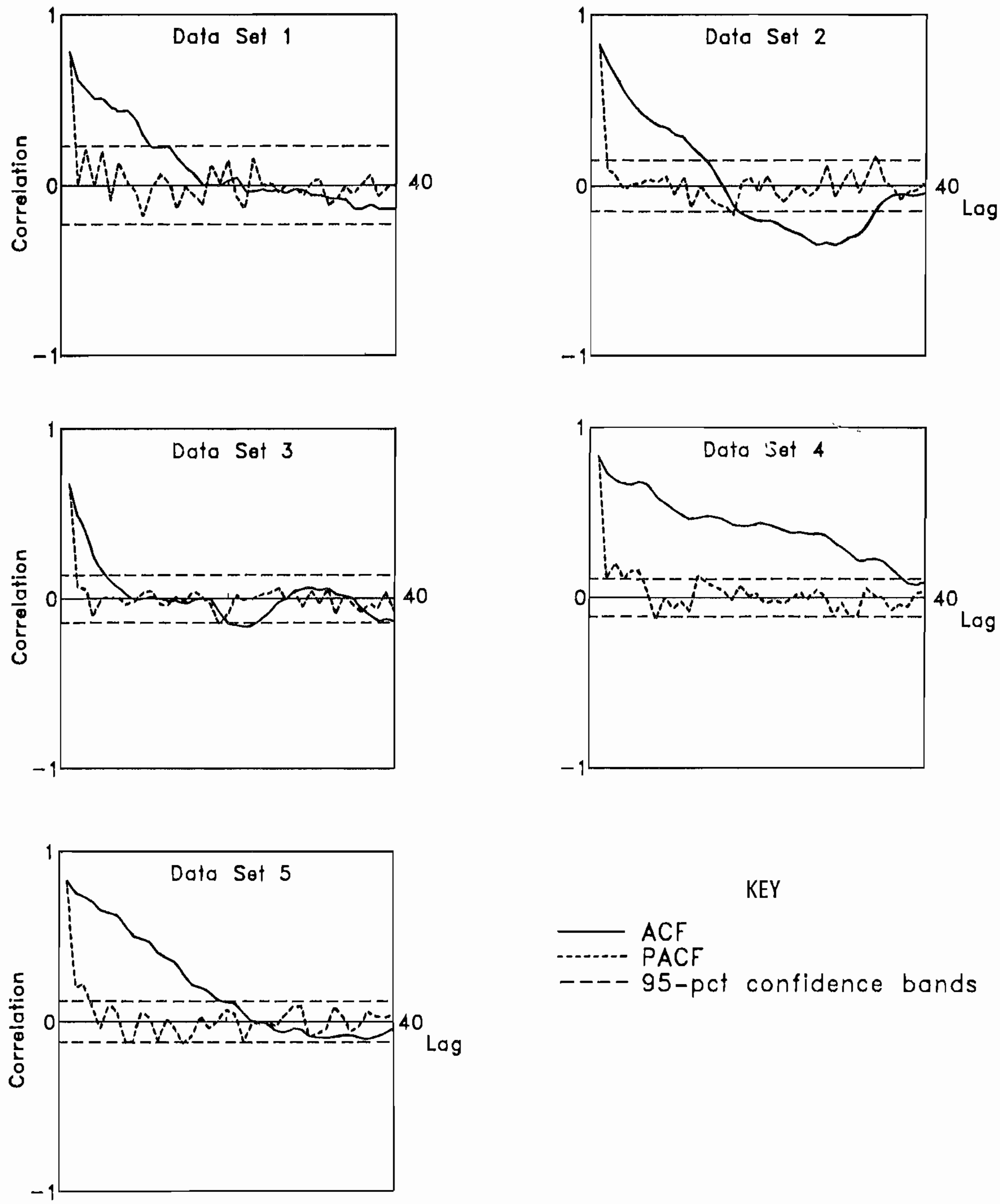

Figure B-1.—Sample autocorrelation functions (ACF) and sample partial autocorrelation functions (PACF) for five log-transformed data sets. Ninety-five pct confidence bands have also been plotted.

Table B-1.—Statistical results from which ARMA models were selected

Data set and statistic	ARMA model					
	AR(1)	AR(2)	AR(3)	AR(6)	ARMA(1,1)	ARMA(2,2)
1:						
AIC . .	-113	-110	-111	NAp	-111	-109
BIC . .	-111	NAp	-104	NAp	NAp	NAp
FPE . .	0.208	NAp	0.213	NAp	NAp	NAp
2:						
AIC . .	-391	-390	-389	NAp	-390	NAp
BIC . .	-387	-382	-377	NAp	-382	NAp
FPE . .	0.113	0.113	0.115	NAp	NAp	NAp
3:						
AIC . .	-356	-356	NAp	-355[1]	-356	NAp
BIC . .	-353	-349	NAp	-344	-349	NAp
FPE . .	0.186	0.186	NAp	0.187	NAp	NAp
4:						
AIC . .	-360	NAp	-376	-391	-297	-365
BIC . .	-356	NAp	-367	-379	NAp	NAp
FPE . .	0.317	NAp	0.302	0.287	NAp	NAp
5:						
AIC . .	-195	-203	-218	-223[2]	-177	NAp
BIC . .	-191	NAp	-210	-204	NAp	NAp
FPE . .	0.519	NAp	0.480	0.472	NAp	NAp

NAp Not applicable.
[1]Statistics cited for AR(4).
[2]Statistics cited for AR(8).

Table B-2.—Listing of 5-day forecasts for each data set (based on 95% confidence)

Future day	Forecast value
DATA SET 1	
1	182.55
2	165.17
3	151.56
4	140.61
5	131.76
DATA SET 2	
1	739.81
2	614.12
3	522.96
4	455.23
5	403.87
DATA SET 3	
1	158.06
2	163.86
3	168.01
4	170.89
5	172.78
DATA SET 4	
1	13.42
2	17.00
3	19.71
4	22.18
5	21.28
DATA SET 5	
1	123.22
2	115.35
3	111.27
4	105.43
5	96.74

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