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MICROSEISMIC APPLICATIONS FOR MINING... A PRACTICAL GUIDE

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16. Abstract (Limit: 200 words)

Increased application and interest in the use of microseismic monitoring to deal with ground control problems, particularly those resulting in violent failures, has brought about the need for practical guidelines with respect to all phases of microseismic monitoring. This report presents the results of an 18-month effort to review the microseismic method and develop needed practical guidelines.

17. Document Analysis a. Descriptors

Mining
Microseismic events	Amplifiers	Microprocessors
Acoustic emissions	Cables	Source location
Transducers	Data processors	Equipment installation

b. Identifiers/Open-Ended Terms

Microseismic equipment
Microseismic monitoring
Microseismic data analysis

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FOREWARD

This report was prepared by Wilson Blake, Consulting Mining Engineer, Hayden Lake, Idaho, under USBM Contract No. JO215002. The contract was initiated under the Metal and Nonmetal Health and Safety Research Program. It was administered under the technical direction of the Spokane and Denver Research Centers, with Mr. J. R. McVey and Mr. F. W. Leighton acting as the Technical Project Officers. Mr. A. M. Lechuga was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period November 24, 1980, to June 23, 1982. This report was submitted by the author on July 12, 1982. No patentable features resulted from this research.

CONTENTS

CHAPTER 1

THE MICROSEISMIC METHOD

The popping and cracking of the rock accompanying the excavation of some underground openings has long been recognized by miners as a measure of the stability of the rock surrounding that opening. Any sudden anamolous change in this "rock talk" was generally interpreted as a sign of potentially unstable conditions. This would normally result in the miners leaving the face to allow the rock to settle down. Though this phenomena of rock talk or rock noise has been reported for many years, not until the late 1930's was special listening equipment developed which allowed an estimate of rock structure stability based on an analysis of detected rock noise.

Introduction and Background

The microseismic method had its beginning in 1938 when the U. S. Bureau of Mines conducted research to determine whether a relationship could be established between seismic velocity and pillar load. Two seismic geophones were placed in a pillar at a predetermined separation and a seismic wave caused to propagate along the pillar. From the time it took this wave to travel between geophones a seismic velocity could be calculated. It was postulated that high pillar loads would be reflected by higher than normal seismic velocities. During these tests it was noticed that spurious seismic signals at a rate of 4 or 5 a minute, were apparently being generated within the pillar. It was inferred that these naturally occurring seismic signals were related to high stress conditions in the pillar (1).[1]

Similar tests in a deep copper mine detected these same self-generated seismic signals. In this case the correlation with high stress was apparent. During the test, ground that had been quiet became seismically noisy, and this noise increased for some 15 minutes before terminating with a rock burst some 50 feet from the test site. It was postulated that if a period of this seismic noise always preceded rock bursting, its detection might be used to forewarn of rock bursts (2).

Based on these findings, the Bureau of Mines began laboratory and field tests to learn more about the occurrence of these self-generated seismic signals. Laboratory tests showed that rock specimens stressed in a testing machine did emit these seismic signals (subaudible rock noise), and the number of these rock noises increased dramatically as failure approached (3), as shown on figure 1-1. Hence, this became the basis for the microseismic method of determining rock stability.

1. Underlined numbers refer to references at end of chapter.
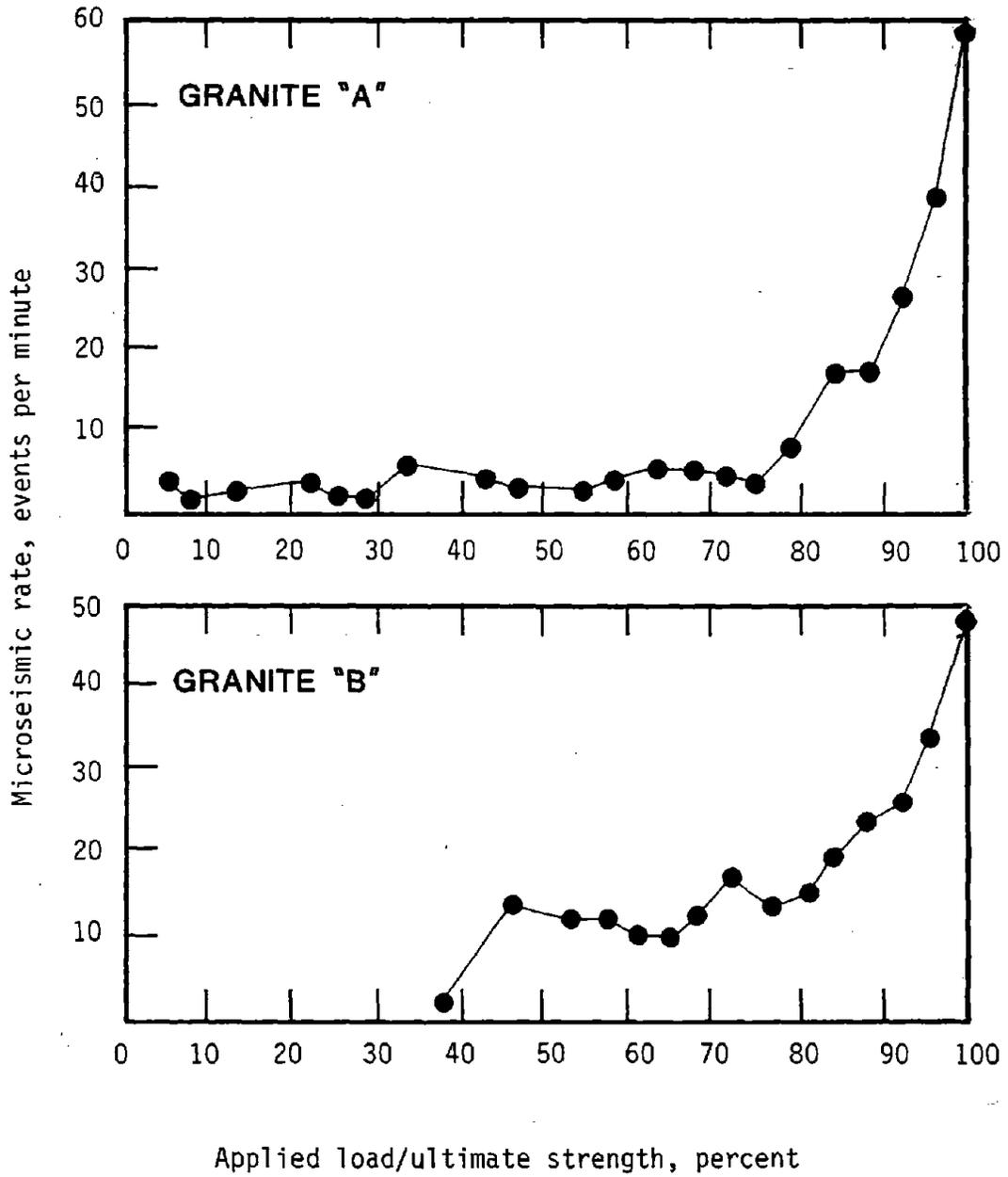
FIGURE 1-1— TYPICAL INCREASE IN MICROSEISMIC ACTIVITY
PRIOR TO FAILURE (3)

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The microseismic method is based on the fact that rock under load responds by making small-scale displacement adjustments to reach a state of equilibrium. If equilibrium cannot be reached, these adjustments become more frequent and are characterized by the release of seismic and acoustic enery--audible rock noise. In addition to these audible noises, a much larger amount of sub-audible rock noise is produced that can be detected only with sensitive geophysical equipment.

The initial microseismic listening equipment was quite simple. It consisted of a geophone to detect the rock noise vibration and convert it to an electrical signal, an amplifier to increase the level of the signal up to 10^5 times, and a head set for listening to the amplified signal.

Early field application of the microseismic method consisted of monitoring or "listening" to suspected unstable rock structures. The number of rock noises detected was counted and from this a microseismic rate was determined -- usually the number of noises per minute. A low steady rate, less than a few per minute, was presumed to be the stable background rate. A high rate, greater than 10 per minute, was indicative of potentially unstable conditions. Any sudden and dramatic increase in microseismic rate (10-to 20-fold) was interpreted as indicating a nearby rock structure failure was likely, and probably imminent.

Early Use and Failure Prediction

Initial field use of the microseismic method was directed towards prediction of rock bursts. This work was carried out in the U. S. by the Bureau of Mines (4), and in Canada by the Federal Department of Mines (5). While it was hoped that all rock bursting would be preceded by an easily recognizable and dramatic increase in the microseismic rate, it was found to be not so clear cut in practice. This is best illustrated by figure 1-2 which shows the results of microseismic monitoring in a burst prone mine in Northern Michigan. It should be noted the "predictions" were not made during actual monitoring, but after the fact using burst criteria based on detailed analyses of the data. During the 40-day monitoring period 14 predictions would have been made; 9 predictions would have been followed by bursts, 5 predictions would not have been followed by bursts, and 2 bursts would not have been predicted. It was concluded both in the U. S. and Canada that the microseismic method was not accurate enough for routine, practical rock-burst prediction.

The microseismic method was also being used in a number of hard rock mines to detect unstable pillars and loose roof. The procedure was to monitor active working areas in a mine by inserting geophones into drill holes in pillars or walls and listening for 15 to 30 minutes. Stable conditions were reflected by low microseismic rates, and unstable conditions were characterized by high and increasing noise rates. Plots of microseismic activity for different mine structures were normally maintained so that trends in the data could be seen.

-12-
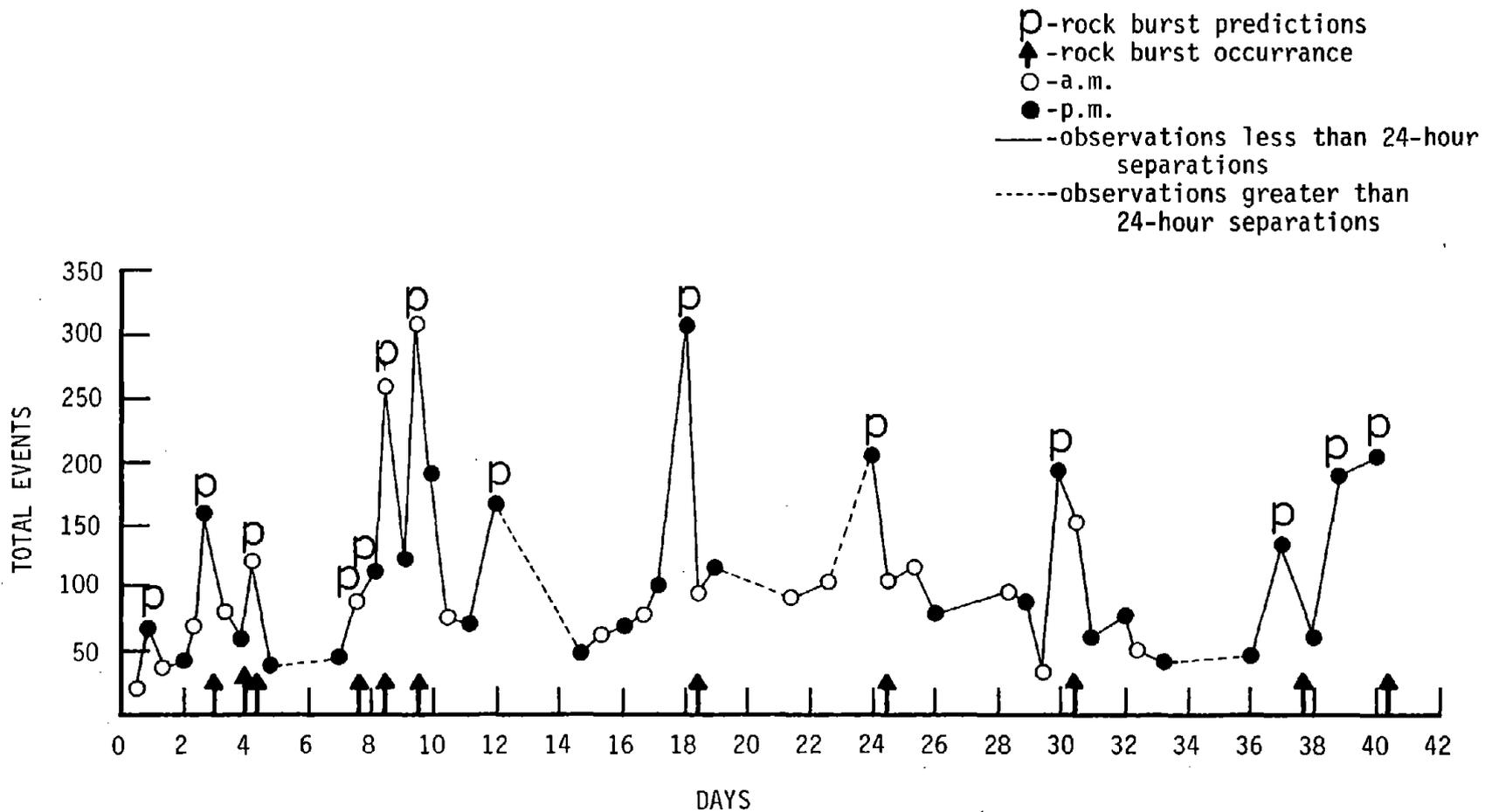
FIGURE 1-2— FORTY-TWO DAY CHART OF SUBAUDIBLE NOISES AHMEEK MINE, 44th level stope(4)

The success of most microseismic monitoring largely depended upon the listener's knowledge and enthusiasm. With a little experience an operator could easily distinguish rock noise from mine and cultural noise. In fact, some operators became very good at judging whether the rock noise was from a pillar or from the surrounding rock. An experienced operator could monitor during mining activity, but usually monitoring was conducted between shifts or during lunch or dinner breaks when mining activity was curtailed or at a minimum. While the microseismic method showed real potential, determination of a true rock noise event and its location was frought with uncertainty.

Publication of the initial Bureau of Mines results led to use of the microseismic method throughout the world in both hard and soft rock mines and civil engineering excavations. Monitoring procedures were essentially unchanged except that single channel monitoring was often replaced by multigeophone monitoring, with the output of the amplified geophones recorded on slow-speed chart paper. This not only allowed monitoring of a larger area but, enabled observers to make judgments about the origin and relative size of individual rock noise events. It was presumed that when an event was detected by more than one geophone the channel reflecting the greatest amplitude was nearest the source. This type of recording made determination of a true rock noise event easier, since most events would appear coincidentally on two or more channels. Furthermore, recording intervals could be programmed on timers, which eliminated the need for manned monitoring.

However, the overall results of these monitoring efforts remained the same -- it was too subjective and qualitative to be reliably used for delineating high stress or potential failure zones. There were some notable infrequent successes, but by only a few special operators. Hence, after nearly 20 years of use, the microseismic method was still regarded as more of a novelty than an engineering tool. It had not really advanced beyond its initial, early successes, despite considerable usage and continued research by the Bureau of Mines (6).

During this period the same phenomenon was independently discovered in metals and referred to as acoustic emissions. Acoustic emission research in metals rapidly expanded, enjoying somewhat greater success than that achieved with microseismic monitoring in geologic media.

Using the results of microseismic or acoustic emission monitoring, whether in rock or metal, one could say only that a potentially unstable condition existed. Generally it was impossible to pinpoint or delineate the unstable zone, and when a failure was expected it was essentially impossible to predict its time of occurrence.

Evolution and Refinements

With the coming of the space age in the early 1960's and resulting availability of solid state, off-the-shelf, electronic components, both microseismic and acoustic emission techniques became more sophisticated. Single-channel monitoring with 1940 vintage equipment gave way to multiple channel monitoring on magnetic tape. The fact that a single rock noise or acoustic emission event could be detected by a number of geophones prompted researchers to try determining the source location by triangulation. On the Witwatersrand in South Africa, Cook used an array of 14 velocity gage geophones to locate the source of large seismic events and rock bursts accompanying deep mining (7). His data was recorded on medium speed magnetic tape, and source locations were determined from the first arrival times of the seismic wave at each geophone. He combined this information with the geophone coordinates and used a string model analogue to calculate the source coordinates. He reported that most of the seismic activity released by mining was located in the solid rock immediately ahead of the working face.

In the mid 1960's the Bureau of Mines reactivated microseismic research because of increasing interest by both mining and construction companies in the microseismic method. A broad-band microseismic system was developed for determining microseismic event source locations in the field (8). Using this new equipment and new data analysis procedures it was possible to detect, locate and plot the source of each microseismic event (9,10). From such studies in deep mines it became possible to delineate high stress zones, potential rock burst zones, and to recognize some characteristic patterns that lead to rock bursting, as shown on figure 1-3. Concurrent research on rock bursting demonstrated that in certain instances bursting could be controlled in mine pillars by drilling and blasting destress holes (11). The microseismic method proved invaluable in evaluating the results of destressing efforts. Seeing the potential of this research as a practical tool for deep mining, the Bureau of Mines developed an automatic rock-burst monitoring system which they called an RBM (12). This was followed by development of a minicomputer monitoring system which the Bureau of Mines still uses in research investigations.

Laboratory studies utilizing source locations of generated microseismic events in specimens under increasing load showed that it was possible to map the location of microfractures. Furthermore, under increasing stress, these isolated microcracks began to group and coalesce along the eventual major failure plane (13, 14). During this same period acoustic emission researchers working in metals developed similar monitoring equipment to study the behavior of vessels under high pressure. They affixed an array of detectors or pickups on the outside of the vessel to detect and locate acoustic emissions as the vessel was pressurized. With high speed electronic counting and processing equipment it was possible to detect and locate acoustic emissions at rates up to
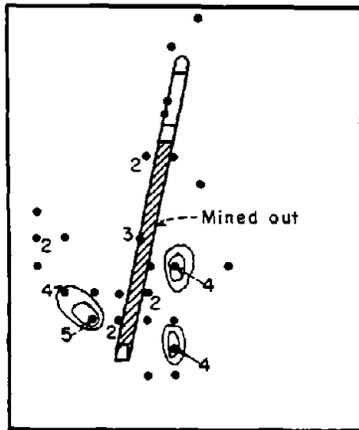
June 25 – July 9
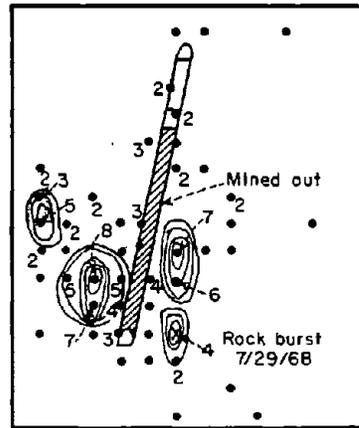
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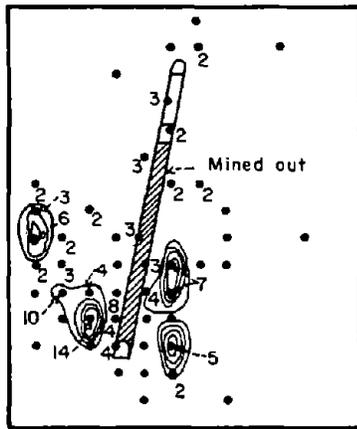
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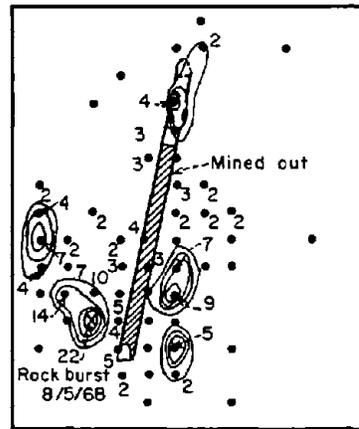
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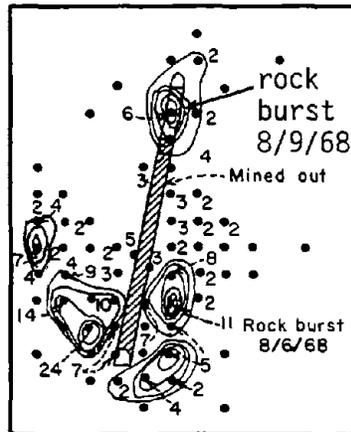
• Source location
3 Number of events

June 25 – Aug 16

FIGURE 1-3— CUMULATIVE PLOTS OF ROCK NOISE SOURCE LOCATIONS,
76R, 3400 to 3200 LEVELS, GALENA MINE (9)

thousands per second. A minicomputer controlled this type of monitoring system and displayed source locations and event rate counts for different areas of the vessel on a TV screen in real time.

The ability to locate the source of a microseismic or acoustic emission event essentially revolutionized the microseismic method. This led to rock burst monitoring in deep hard rock mines, coal bump monitoring in deep coal mines, location of trapped miners, mapping of hydrofractures, etc. Also, microseismic monitoring of surface structures, such as open pit mines, has been used to detect and locate potential sliding planes.

Meanwhile, traditional microseismic monitoring with single channel equipment continued in both underground and surface excavations. Though these efforts weren't generally as successful as monitoring with locating systems, the use of the microseismic method in evaluating the stability of landslides or cut slopes proved to be effective (15,16,17). The most noteworthy of these efforts was the work routinely carried out by the California Hiway Department to evaluate slide zones (18). Here it was shown that high microseismic rates were indicative of a moving or unstable slope. In some cases road closures through landslide areas were based on the results of this monitoring.

By the end of the 1960's the microseismic or acoustic emission methods were being successfully used in both mining and civil applications in both underground and surface excavations. In addition, laboratory studies of both rocks and metals provided needed and useful data with respect to the behavior of these materials under load. The microseismic method had finally become of age as a useful engineering tool.

Engineering Tool for Mining and Civil Excavations

The use of microseismic or acoustic emission techniques for determining the stability of structures is now well accepted in mining, civil and metallurgical fields; however, its most successful application remains in rock burst monitoring. Patterned after the Bureau of Mines RBM system, the first industrial owned computer controlled microseismic monitoring system was developed in 1972 by the Hecla Mining Company for use at their Lucky Friday Mine. Since then mining companies have installed rock burst monitoring systems in the Western Deep Level Mine in South Africa, the Sunshine, Star, Galena and Crescent mines in the Coeur d'Alene mining district of North Idaho, Mount Isa Mine in Australia, the East Malartic, Creighton and Falconbridge mines in Canada, and the El Teniente Mine in Chile.

Data from these monitoring systems are used to delineate high stress and potential burst zones and evaluate rock burst control measures. Based on a sudden increase of microseismic activity during working hours, as shown on figure 1-4, miners have been evacuated from stopes prior to the occurrence of a rock burst (20). Although it is not difficult to delineate burst-prone areas, the time of occurrence of fewer than 10 rock bursts worldwide have been accurately predicted with the present state of the art. Data from monitoring is most often used to determine where and when destress blasting or a mining change may be necessary to improve rock burst control. Figure 1-5, a plot of microseismic energy released by mining in two burst-prone stopes, indicates that destressing a floor prior to mining greatly reduced the seismic hazard (21). Without microseismic monitoring it is almost impossible to quantitatively assess improvements in rock burst control resulting from mining changes.

Microseismic monitoring in underground coal mines has reached an equally high level of sophistication. Poland, Czechoslovakia and West Germany have extensive automatic monitoring programs in progress with very encouraging results in improving ground control and reducing the hazard from coal bumps (22, 23, 24). In the U. S. The Bureau of Mines and Pennsylvania State University have been conducting similar monitoring programs (25, 26).

In the civil engineering field, microseismic or acoustic emission monitoring has been found useful in a wide variety of applications. Stability monitoring of large underground storage cavities, particularly those containing a pressurized gas, has great potential for detecting and locating any potential failure zones (27). The monitoring of earth dams and embankments is rapidly becoming routine as a result of the research and field studies carried out under a Bureau of Mines contract by Drexel University over the past few years (28, 29).

In addition to field studies in the low to moderate frequency ranges, 10 - 10,000 Hz, an increasing number of studies are being conducted at much higher frequencies. Monitoring in the 35+ KHz range has been successfully used to detect potential outburst zones and roof fall areas in coal mines (30,31).

It should be noted that single channel listening is still providing effective results in a number of mining and civil applications. Although the data from this type of monitoring may be more qualitative than quantitative, there are advantages to having portable instrumentation that can be easily transported to any particular suspected problem area and immediately put into service.

Besides field applications, microseismic or acoustic emission monitoring studies are proving to be very useful in studying the mechanisms of rock failure. Much of this work is being carried
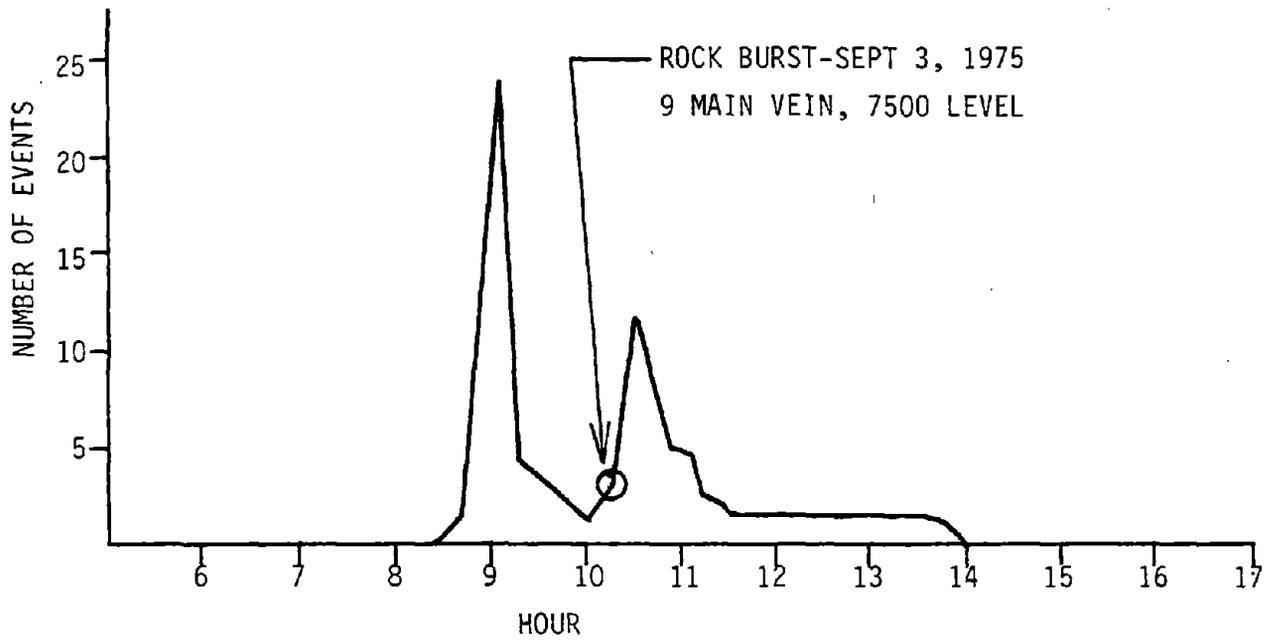
FIGURE 1-4—ACOUSTIC EMISSION RATE PRIOR TO A MAJOR ROCK BURST, STAR MINE (20)
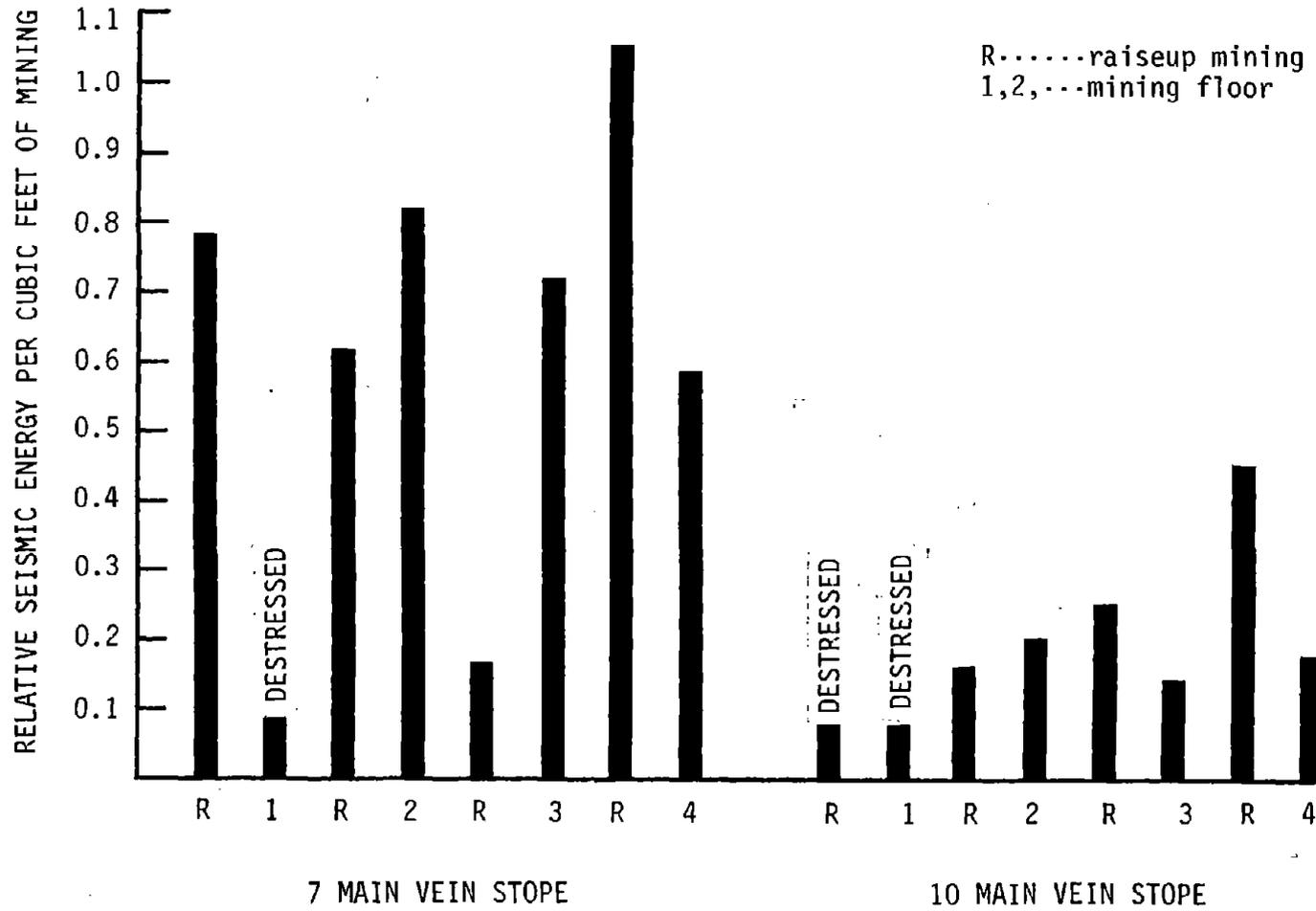
FIGURE 1-5— SEISMIC ENERGY VERSUS MINING 7700 LEVEL, STAR MINE (21)

out by the U. S. Geological Survey in conjunction with their earthquake research (32, 33).

The level of sophistication of the latest microseismic or acoustic emission monitoring equipment has presented problems for mine operators or construction contractors in finding personnel with the training and background needed for installation, maintenance and operation.

Need for Microseismic Handbook

Mining and construction companies throughout the world have shown great interest in using microseismic monitoring to deal with specific ground control problems. They have resources for purchase but have expressed concern or experienced difficulty in finding and maintaining staff knowledgeable enough to develop, install and adequately operate a microseismic or rock burst monitoring system.

Because most applications differ with respect to site, conditions and purpose, monitoring systems are generally tailored to suit a particular use; hence, the selection of the components of a system is critical. Also, even the most sophisticated state-of-the-art microseismic monitoring system will not function properly if not installed correctly. The choice of the number of geophones and their location is critical for accurate source location. Furthermore, the proper operation of a microseismic monitoring system is the key to obtaining usable data.

This publication has been prepared because of industry's need for practical guidelines dealing with all phases of microseismic monitoring.

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CHAPTER 2

PROPERTIES OF MICROSEISMIC EVENTS

The mining of underground openings changes the stress field immediately ahead of an advancing face. The new heading is subjected to stress increases of from 2 to 5 times the premining stresses. The rock responds by deforming, and, if the loads are high enough, by cracking.

Microseismic Activity

Microseismic activity is generated by the deformation and cracking of the rock around an opening as it tries to achieve equilibrium under a new geometry or changing stress conditions. If equilibrium is reached, the deformation and accompanying microseismic activity cease. If equilibrium is not reached, deformation and microseismic activity continue. If the deformation process leads to instability and rock failure occurs, the microseismic activity increases dramatically -- with respect to both frequency of occurrence and intensity (magnitude).

A specific mechanism that initiates a microseismic or seismic event is not readily determinable. Whether it is sliding, cracking, shearing, crushing, etc., can rarely be determined -- and then only by rather complicated and time-consuming studies.

Fundamental Properties

Microseismic activity is generally characterized by a set of parameters associated with the occurrence of a single microseismic event or a group of events. Some commonly used parameters are defined as follows:

1) Total Events or Accumulated Activity -- The total number of events detected during a specific time interval.

2) Microseismic Rate or Rock Noise Rate -- The number of events detected per unit time.

3) Microseismic or Peak Amplitude -- The maximum amplitude of a recorded event in arbitrary units.

4) Microseismic Energy -- A measure of the magnitude of a detected event as determined by any of a number of methods.

5) Total Energy or Accumulated Energy -- The sum of the energy released by all events detected during a specific time interval.

6) Energy Release Rate or Energy Rate -- The sum of
    the energy released by all events detected per
    unit time.

7) Energy per Event -- The total energy divided by
    the total events detected during a specific time
    interval.

Parameters associated with the waveform of a microseismic event
are shown on figure 2-1. Note that the threshold level is ar-
bitrary, normally set equal to two or three times the background
noise level.

    The frequency spectrum of microseismic events is very broad.
Small events associated with the formation of microcracks have
frequencies in the 10^5 to 10^6 Hz range. Large events, such as
rock bursts, are made up of frequencies in the 10^2 to 10^3 Hz
range. It is apparent that, depending on the volume of rock in-
volved and the source mechanism for releasing the seismic or
microseismic energy, the frequency of an event can vary greatly
with respect to both location and time. To further complicate
the frequency characteristics of microseismic events, the earth
acts as a low pass filter; hence, high frequency components of
any event are rapidly attenuated. Figure 2-2 shows the fre-
quency ranges over which seismic and microseismic studies are
most commonly conducted. Figure 2-3 shows frequency spectrums
for typical microseismic events detected in field studies, in-
dicating that waveform of an individual event is made up of a
wide range of frequency components. Figure 2-4 shows how in-
creased travel time or distance attenuates the high frequency
components of a microseismic event detected at 2 geophone
locations separated a few hundred feet.

    Pulse durations of microseismic events vary from micro-
seconds for very small high frequency events up to tens of
seconds for large rock bursts. Most microseismic events are
low level with respect to energy release. The magnitude and
energy level of microseismic and seismic events depend on the
volume and characteristics of the rock that was overstressed
and suddenly failed or displaced, releasing stored strain
energy. The formation of a microcrack releases energy in the
10^6 ft -lb range; whereas major rock bursts have been as large
as 5+ on the Richter earthquake scale. Thus, the energy re-
leased in a microseismic event can vary from something barely
detected with sensitive geophysical equipment to something
felt and heard over tens of miles. In general, the larger
the event the lower the frequency, and for all events most
of the energy is contained in the lower frequency components
of the seismic or microseismic wave.
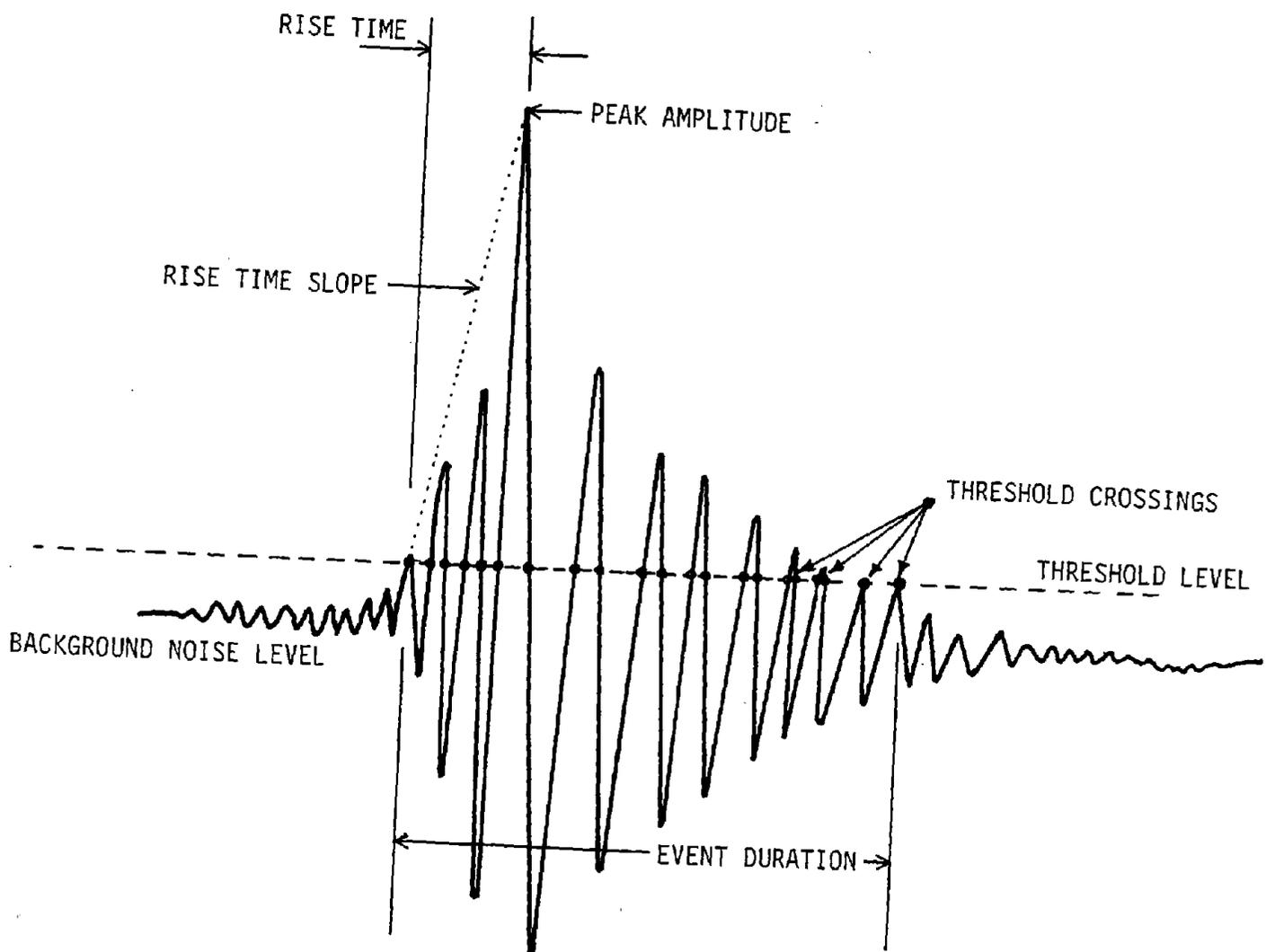
FIGURE 2-1—MEASUREMENT PARAMETERS ASSOCIATED WITH A MICROSEISMIC WAVEFORM
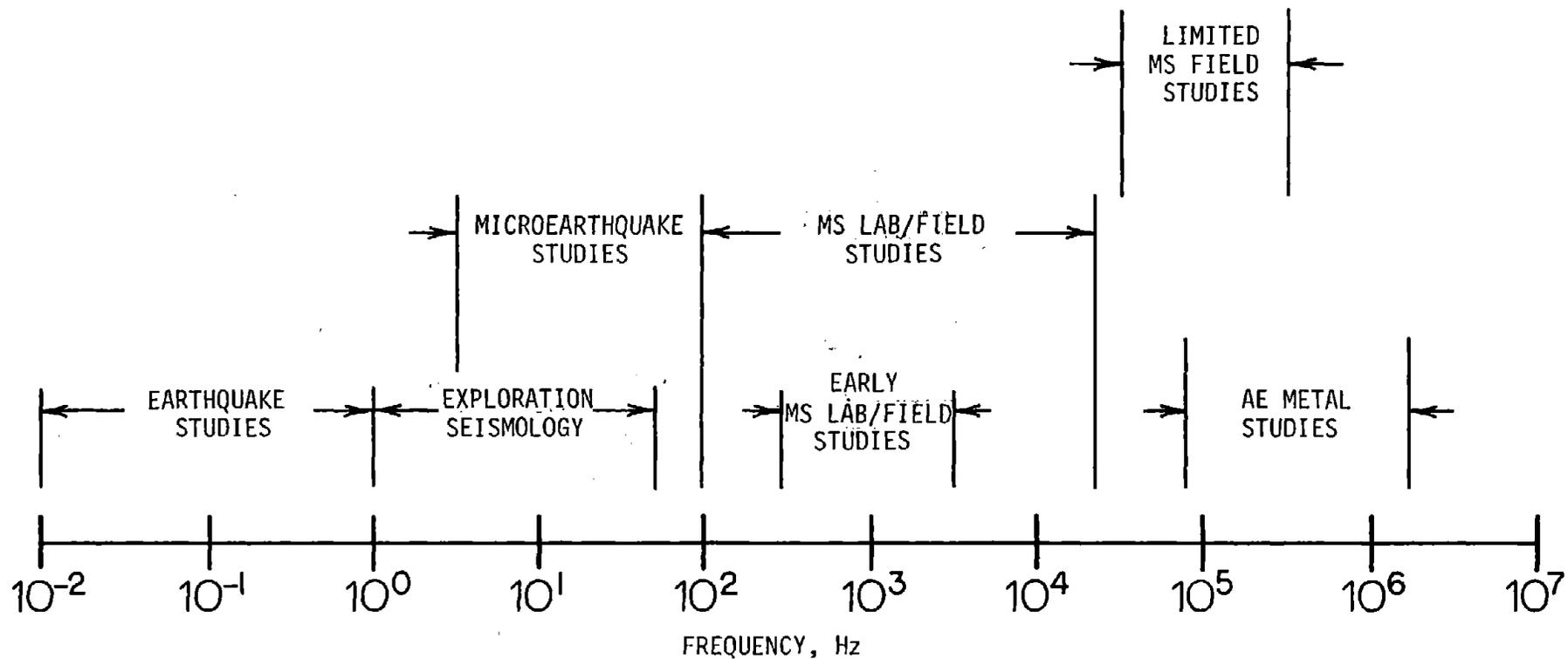
FIGURE 2-2— FREQUENCY RANGE FOR SEISMIC AND MICROSEISMIC MONITORING [after (1)]
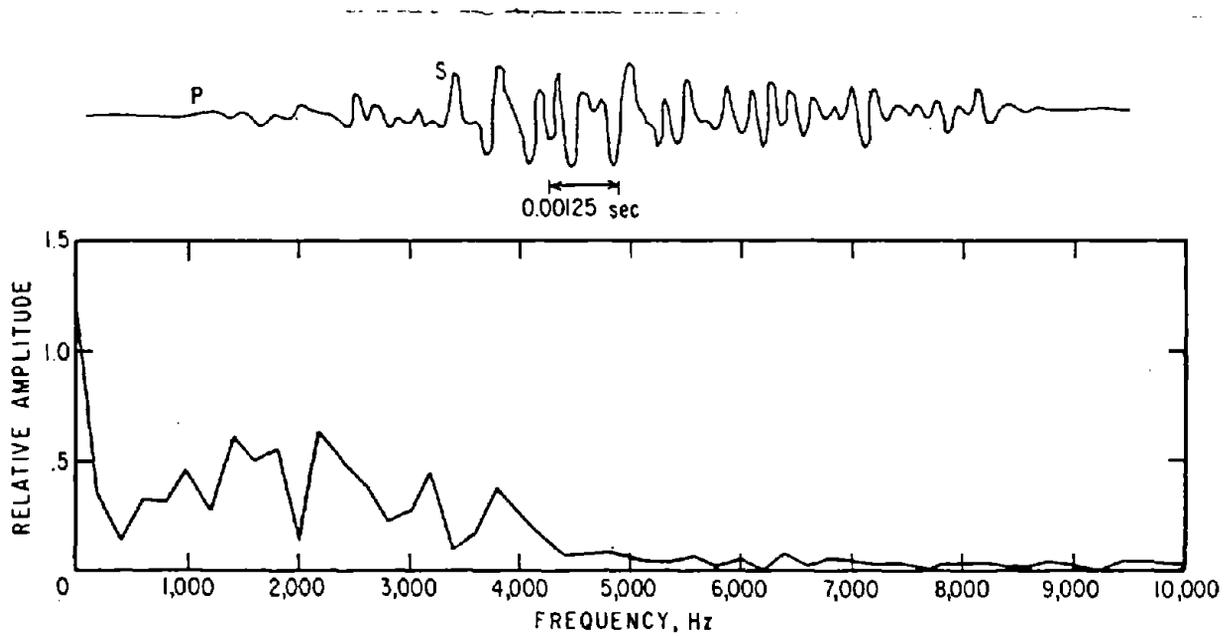
A- medium frequency rock noise waveform and it's frequency spectrum
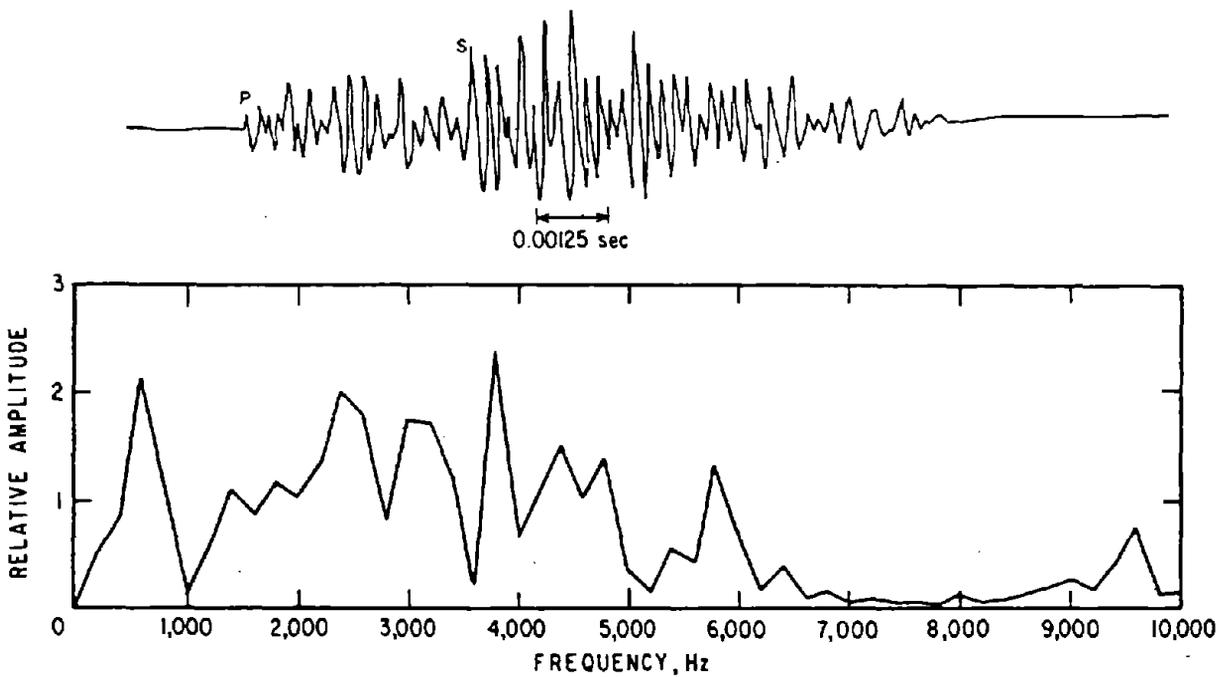
B- high frequency rock noise waveform and it's frequency spectrum

FIGURE 2-3— FREQUENCY SPECTRUM OF ROCK NOISE EVENTS (2)

FIGURE 2-4— EFFECT OF INCREASED TRAVEL DISTANCE ON THE FREQUENCY OF A ROCK NOISE (2)

Whereas, the waveform of a microseismic event is very complex, containing high and low frequency components, it is generally possible to distinguish both P (compressional) and S (shear) waves. The P-wave is always the first arrival wave since it propagates at a higher seismic velocity than the S-wave. (See Richter's "Elementary Seismology" (3) for a basic treatment of siesmic waves.) Most of the energy associated with microseismic events resulting from changing mine geometry appears to be in the S portion of the wave.

Application to Monitoring

Ideally, microseismic monitoring equipment should be sufficiently broad band to respond to all frequencies. This equipment should also have enough dynamic range to detect all events from microcracking through rock bursting. Because of equipment and economic limitations, it is not possible to build a monitoring system suitable for all applications. Consequently, one must generally design the monitoring equipment to match the characteristics of the microseismic events generated at any particular site. That is, the frequency response, dynamic range and amplification of the monitoring system must be capable of detecting and processing a majority of the events occurring at a mine or within a particular study zone. Furthermore, the severity of the problem and the purpose of the monitoring should be taken into account when developing a monitoring system, as the costs and hazard resulting from potential failures usually dictate the sophistication of the system.

To select the proper components of a microseismic monitoring system, one must first conduct a test program to determine the characteristics of the microseismic events being generated on site. This can be done with a single broad-band geophone, amplifier and storage oscilloscope, or with multichannel recording on magnetic tape. From such a test program, the frequency range, magnitude range, attenuation characteristics and propagation velocities of the microseismic events can be determined. An example of a good test program to determine the characteristics of microseismic events at a site prior to developing and purchasing a microseismic monitoring system is the program that was carried out by Mount Isa Mines in Australia (4). Before discussing test programs a description of microseismic equipment is necessary.

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1. Hardy, H. R., Jr. Application of Acoustic Emission Techniques to Rock Mechanics Research. Acoustic Emission, ASTM, STP 505, 1972, pp. 41-83.

2. Blake, W., F. W. Leighton and W. I. Duvall, Micro-seismic Techniques for Monitoring the Behavior of Rock Structures. Bu Mines Bull. 665, 65 p., 1974.

3. Richter, C. F. Elementary Seismology. W. H. Freeman and Co., San Francisco, CA, 1958, pp. 316-323.

4. Godson, R. A., M. C. Bridges and B. M. McKavanagh. A 32-channel Rock Noise Source Location System. Proc. Second Conf. AE/MS Activity in Geologic Structures and Materials, Penn. State Univ., November 1978, Trans Tech Publications, 1980, pp. 117-161.

CHAPTER 3

MICROSEISMIC EQUIPMENT

Seismic, microseismic and acoustic emission monitoring systems perform essentially identical functions. They all detect and record or register ground motions produced by sudden shock displacement or failure within a rock mass or other material.

Components of a Microseismic System

The basic components of a microseismic system are shown on figure 3-1.

Geophones

A point in a rock mass moves up and down and back and forth as a transient seismic wave passes through the point. These ground motions can be measured with respect to rock particle displacement, velocity and acceleration with time. Velocity gages and accelerometers are used as transducers for microseismic geophones. The geophone case, attached to the rock mass, moves with respect to its contents when the rock mass is vibrated by a passing seismic wave.

a. Velocity Gages

Velocity gages consist of a case containing a suspended coil and a fixed magnet (figure 3-2). Ground vibrations cause this magnet to move with respect to the coil in a way that generates a voltage proportional to the particle velocity, or rate of particle displacement. Velocity gages are constructed to respond to vertical or horizontal vibrations, therefore, the gage orientation must correspond to the direction of motion to be sensed.

Typical specifications of a velocity gage transducer would include:

Size	: diameter	1.25	in
	: length	1.32	in
	: weight	3.9	oz
Core	: weight	0.57	oz
	: displacement	0.1	in

Sensitivity : 1.0 v/in/sec
Coil resistance : 870 ohm
Natural frequency : 8 Hz
Frequency response: 10 - 2500 Hz ($\pm$ 5%).

GEOPHONE

OUTPUT

| TRANSDUCER | → | PRE-AMP |

CABLE

SIGNAL
CONDITIONING
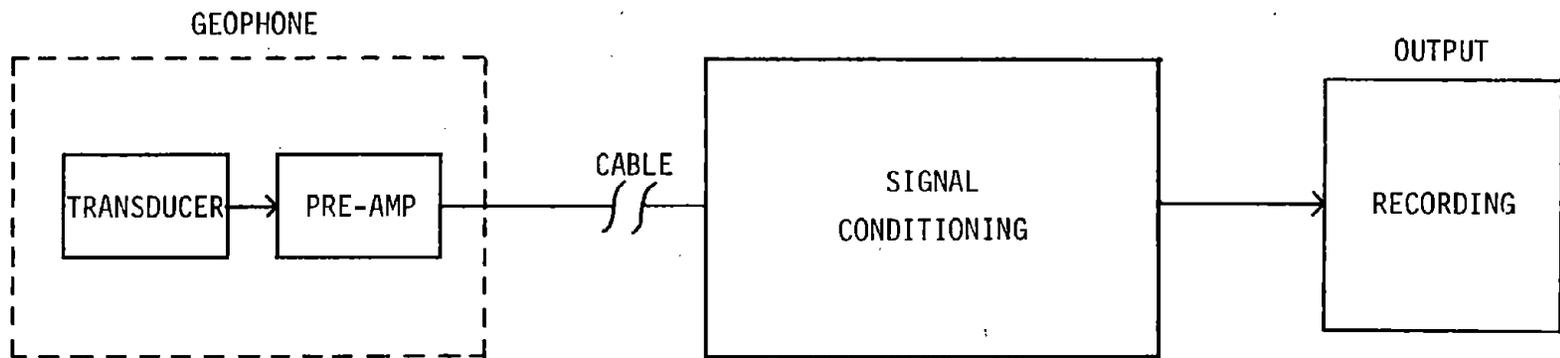
RECORDING

FIGURE 3-1— BASIC COMPONENTS OF A MICROSEISMIC SYSTEM

The low output impedance of a velocity gage is desirable because it can be readily matched to most amplifiers or recording equipment. The sensitivity (output) of the transducer must be high enough to allow detection of the desired rock noise activity. Selection of a high output transducer can sometimes eliminate the need for high amplification and provides better signal-to-noise ratios. It must be remembered that increased amplification also means increased noise level in a system.

b. Accelerometers

Accelerometers usually consist of a piezoelectric material attached to a suspended mass such that the motion between the case and the mass generates a voltage in the piezoelectric element that is proportional to rock particle acceleration, or rate of particle velocity. (See figure 3-2).

Some essential specifications for a piezoelectric accelerometer might be:

Size	: diameter 1.0 in
	: length 0.9 in
	: weight 3.8 oz
Capacitance	: 135 pF
Sensitivity	: charge 85 pcmb/g
	: voltage 0.35 v/g
Resonance frequency	: 16,000 Hz
Frequency response	: 2 - 3,000 Hz ($\pm$ 5%).

The electrical characteristics of a piezoelectric accelerometer are very different from the previously discussed velocity gage. The piezoelectric accelerometer is a capacitive device which has a very high impedance -- stated as a capacitance value. To match the high impedance output of the accelerometer a charge amplifier or a voltage amplifier with a high input impedance must be used.

Velocity gages and accelerometers are most sensitive to vibrations in the 1 - 2500 Hz and 10 - 50,000 + Hz frequency ranges respectively. For this reason, velocity gages are used for low to moderate frequency work, such as seismic exploration and micro-earthquake studies; and accelerometers are used in higher frequency applications, such as impact or crack detection studies.

Because of the broad frequency-spectrum (10 to 50 + KHz range) of microseismic events, transducers in microseismic geophones are usually velocity gages or accelerometers. Transducers, similar to those shown on figure 3-2, can be purchased with a wide selection of sensitivity and frequency response. For detailed microseismic monitoring a highly sensitive accelerometer is normally used because it is more suited to detect higher signal frequencies.
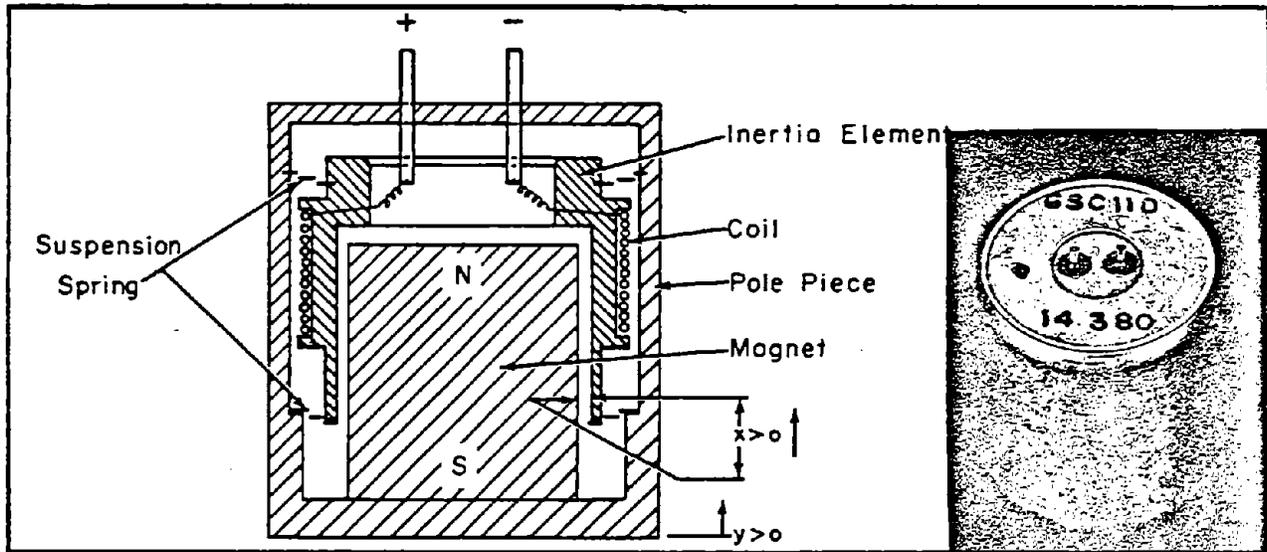
-A-VELOCITY GAGE CONSTRUCTION AND TYPICAL GAGE   (courtesy Geospace Corp)
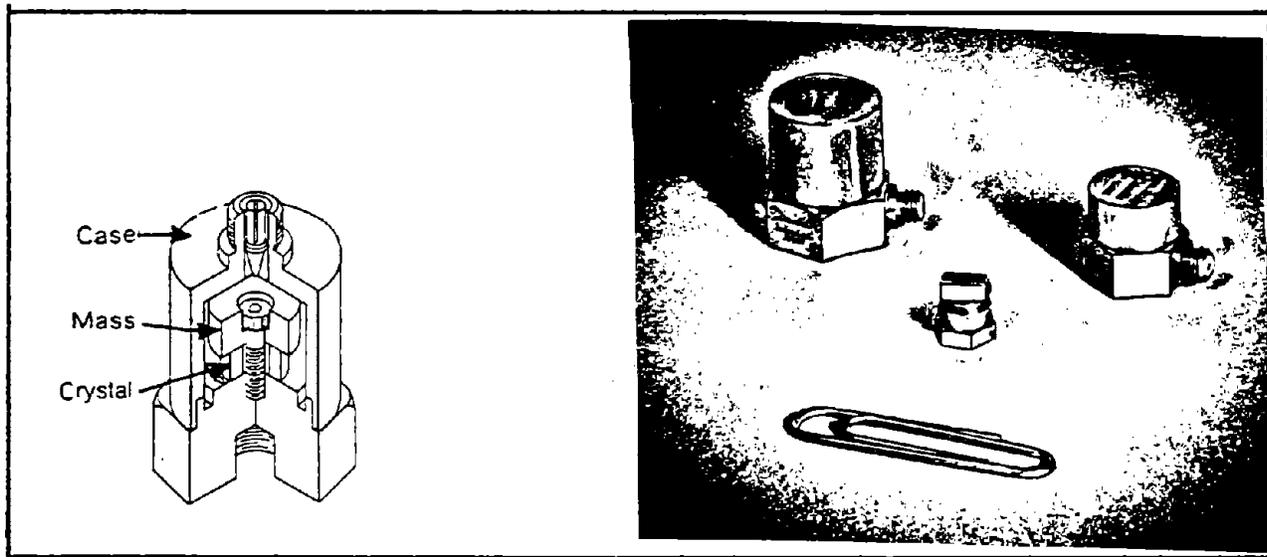
-B-ACCELEROMETER CONSTRUCTION AND ACCELEROMETERS

(courtesy Columbia Research Labs)

FIGURE 3-2— TRANSDUCERS FOR MICROSEISMIC GEOPHONES

-36-

For minewide rock burst monitoring a velocity gage is normally used because of lower signal frequencies. Tests and procedures for determining the most suitable type transducer for a given application are discussed in Chapter 4 and Appendix A.

c. Preamplifier

Virtually all microseismic installations use a preamplifier located at the transducer. For velocity gage transducers the preamplifier is necessary because the gage output is very low level, and this signal might be lost in extraneous noise picked up by the transducer cable and associated connections. For accelerometers the situation is worse, because its impedance is very high, and without preamplification any appreciable cable length will attenuate its output below usable levels.

Impedance between the transducer and the preamplifier must be matched to prevent both power loss and noise generation. Velocity gages, which have a low impedance output, can be connected to either a bipolar or FET (field effect transistor) type preamplifier. Accelerometers, however, because of their high impedance output, should only be connected to FET or charge amplifiers. To accomodate either a velocity gage or accelerometer, a high input impedance (FET) voltage preamplifier is normally used.

The bipolar, single ended preamplifier is a three terminal device having a common input and output terminal. This type of instrumentation amplifier is used in most audio and line driver applications. Typical specifications for an instrumentation preamplifier would include:

Gain	:	1 to 2500 in steps of 1,10,100,1000
Accuracy	:	$\pm$ .01% to $\pm$ .1%
Bandwidth	:	DC to 100 KHz
Input impedance	:	1 to 100 megohms
Output impedance	:	0.1 ohm to 100 ohms
Noise	:	0.5 microvolt p to p at 10 KHz
	:	2.0 microvolt RMS at 10 KHz
		(referred to input)
Common mode	:	120 db DC to 60 Hz $\pm$ 25v
Single ended or differential.		

The FET preamplifier is basically a bipolar amplifier with a high input impedance. Specifications for this type preamplifier would include:

```
Gain               :  10,100 or 1000
Gain stability     :  + 0.1 db
Bandwidth          :  0.1 Hz to 100 KHz
Input impedance    :  1000 megohms
Output impedance   :  30 to 100 ohms
Noise              :  2.0 microvolts over 100 KHz
                      (referred to shorted input).
```

The charge amplifier is basically an FET amplifier with a capacitance feedback loop. This amplifier is designed specifically to be used with very high impedance piezoelectric crystal type transducers. The charge amplifier has an advantage over the voltage type amplifier because its gain is independent of the input and cable capacitances. The gain of a charge amplifier is expressed in mv/pcmb (millivolts per picocoulomb). Some general specifications for a charge amplifier might be:

```
Input connection:  single ended
Source impedance:  50,000 pf maximum
Maximum input    :  + 10,000 pcmb
Gain             :  1 mv/pcmb
Range            :  .01 g to 10,000 g
Accuracy         :  + 1%
Bandwidth        :  0.1 Hz to 10 KHz
Output impedance:  100 ohms maximum
Output voltage   :  + 10v pk, 0.1 Hz to 5 KHz
Residual noise   :  50 microvolts with 1000 pf
Source capacitance
```

The differential amplifier is most often used with transducers having low level ouput signals and where common mode and electrical noise problems are dominant. The unique feature of differential amplifiers is that their rejection voltage is common to both input terminals, thereby cancelling common mode and circuit noise voltages which appear equally at each terminal. This results in only the signal or the differential voltage being amplified. The differential amplifier is best suited for minimizing electrical and grounding noise in applications where low impedance, velocity gage transducers are used. Specifications for differential amplifiers

are the same as those given previously for the bipolar amplifier. A more fundamental treatment of amplifiers and electrical noise problems is given in Appendix B.

The preamplifier should have a fixed gain in the 40 - 60 db range (100 - 1000 gain), a noise level in the 2.0 microvolt range (referred to a shorted input), a flat or uniform frequency response over the frequency range of interest, and low output impedance to transmit signals over long cable lengths without losses. The microseismic geophone, consisting of transducer and preamplifier, must be robust and waterproof and should be compact enough to fit into a 2 - inch diameter hole.

Cables

In most microseismic applications, the geophone or geophone array is placed at some distance from the processing unit; hence, the geophone output signals must be transmitted. A number of transmission means, including wireless and fiber optic, are being investigated for microseismic systems, but presently the metallic electrical cable is the most reliable, economical and widely used. Cables offer both capacitance and resistance to signals being transmitted. A long transmission line acts as a low pass filter with loss. A high frequency signal (fast rise time) becomes more rounded and attenuated as the signal propagates down the line. The resistance of the cable wires also causes an overall reduction in signal amplitude. These combined effects limit the frequency response that can be transmitted by a given type and length of cable. The larger the wire or gage size the less resistance and usually less capacitance. When running long lengths one should select a cable with as low a capacitance and resistance per foot as economically possible, considering size, weight and installation factors.

Microseismic cables must be shielded to prevent electrical field interference and should have a waterproof jacket. Vinyl covered cables are generally not satisfactory for underground installation. Polypropylene covered cables designed for direct burial are preferred. Where water is present, such as in a wet shaft, the cable should be filled to prevent moisture infiltration should the cable jacket become cut or nicked. Also, armoured cable is recommended in areas where cables are vulnerable to falls of rock and/or heavy equipment traffic. For most microseismic applications 20-or 22-gage stranded cable is used.

For single-ended preamplifiers, 3-conductor shielded cable is normally used, since the additional conductor permits transmission of power back to the preamplifier. For differential amplifiers, 4-conductor shielded cable is used so that the transducer signal common ground is isolated from the earth ground. The geophone high and low (common) signal lines are tied directly to the differential inputs of the amplifier, thereby floating the geophone (no ground).

Most widespread underground geophone arrays are cabled
back to the data processing unit through a system of junction
boxes and multipair trunk-line cables. Line operated power
supplies are located underground at these junction boxes to
supply a number of preamplifiers. Wiring procedures are dis-
cussed in a later chapter, and eliminating or minimizing elec-
trical noise in cables is discussed in Appendix B.

Data Processor

Microseismic events that are detected by a geophone or
geophones are converted to electrical signals, preamplified and
transmitted to a data processing unit. The data processor can
be very simple, consisting of only a post amplifer and an out-
put stage for some single-channel, portable systems. On the
other hand, the data processor in a rock burst monitoring sys-
tem is usually very sophisticated. It may contain a signal
conditioning section, a timing and control section, an energy
section, a waveform analysis section, a calculating section and
an output section, as shown in figure 3-3.

The signal conditioning section consists of filtering and/
or post amplification. Depending on their nature and severity,
electrical or mechanical noise at a site may have to be filtered
out because they mask the microseismic signals. Filtering, how-
ever, must not result in the loss of legitimate microseismic
signals. Usually the filtering will cut off unwanted high or
low frequencies, depending on the application. Notch filtering
to eliminate a particular frequency, such as 60 Hz, is not un-
common in low frequency applications. Post amplification is
necessary if the level of preamplified signals is still too low
for detection by processing or recording equipment. This is the
case in most microseismic applications. The exception is in
mine wide rock burst monitoring, where most signal levels are
high enough so that output from a 60-db gain preamplifier need
not be further amplified. Matching the post amplifier to the pre-
amplifier is usually not a problem. For differential preampli-
fier output, a post amplifier or line balancing unit with a diff-
erential input is required. Post amplifiers usually provide a
gain of 80 db (10,000 gain) in 2 to 6 db steps. These amplifiers
should also have low internal circuit noise and broad frequency
response.

The timing and control section of the data processor is
usually a combination of hardware and software to provide:

1) an initial trigger that starts a time window
   when any geophone output exceeds a preset
   threshold voltage,

2) timing of subsequent first arrivals at other
   geophones as threshold voltages are exceeded,

3) a signal to an energy integrating circuit or
   a waveform analysis circuit to operate on the
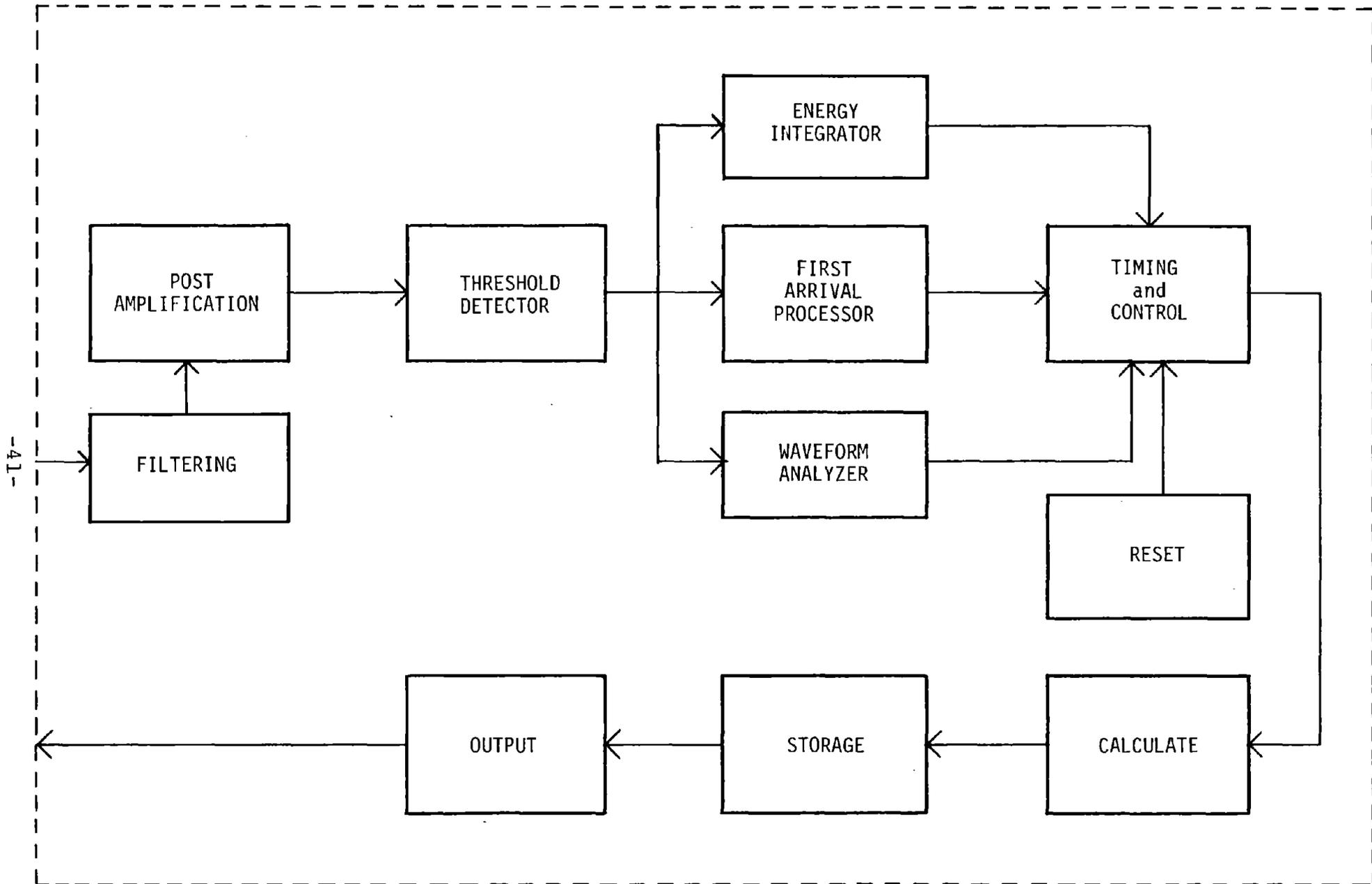
FIGURE 3-3— DATA PROCESSING UNIT

incoming waveform at one or more channels,

4) a determination of whether a minimum number of geophones have been hit during the time window to consider the event real,

5) day, date and time-of-day information regarding the triggering event,

6) a flag at the end of the time window that causes a reset on false events and a data transfer plus reset on good events.

Whereas all this data may be provided for each individual event in a rock burst monitoring system, only day, date and time-of-day may be provided in a single-channel portable system.

The calculating section of the data processor receives data from the timing and control section to determine:

1) x,y,z, source location coordinates for each event,

2) microseismic rates and/or total number of counts or threshold crossings,

3) amplitude, energy and frequency distributions,

4) energy release rates and/or total energy,

5) statistical manipulation of the above data.

Whereas the timing and control section of earlier data-processor units were made up of hardware components, recent trends are towards microprocessor based systems. Where complex or lengthy calculations are necessary, such as in a three dimensional source location system, additional processor capabilities are required.

Output Stage

The output stage of a microseismic monitoring system can consist of a wide variety of display or storage options as shown in figure 3-4. One usually has no problem assembling and analyzing small volumes of data, generated at a slow rate, and making a continuous engineering evaluation of a structure's stability. However, additional computer capability is required for meaningful analysis of large volumes of data generated at a high rate. In this latter case, the outputted data can be transmitted via a direct data-transmission link to an online, interactive minicomputer.

It should be noted that an online minicomputer can be used for other applications or for batch processing on an interrupt and priority-tasking schedule.

OUTPUT STAGE
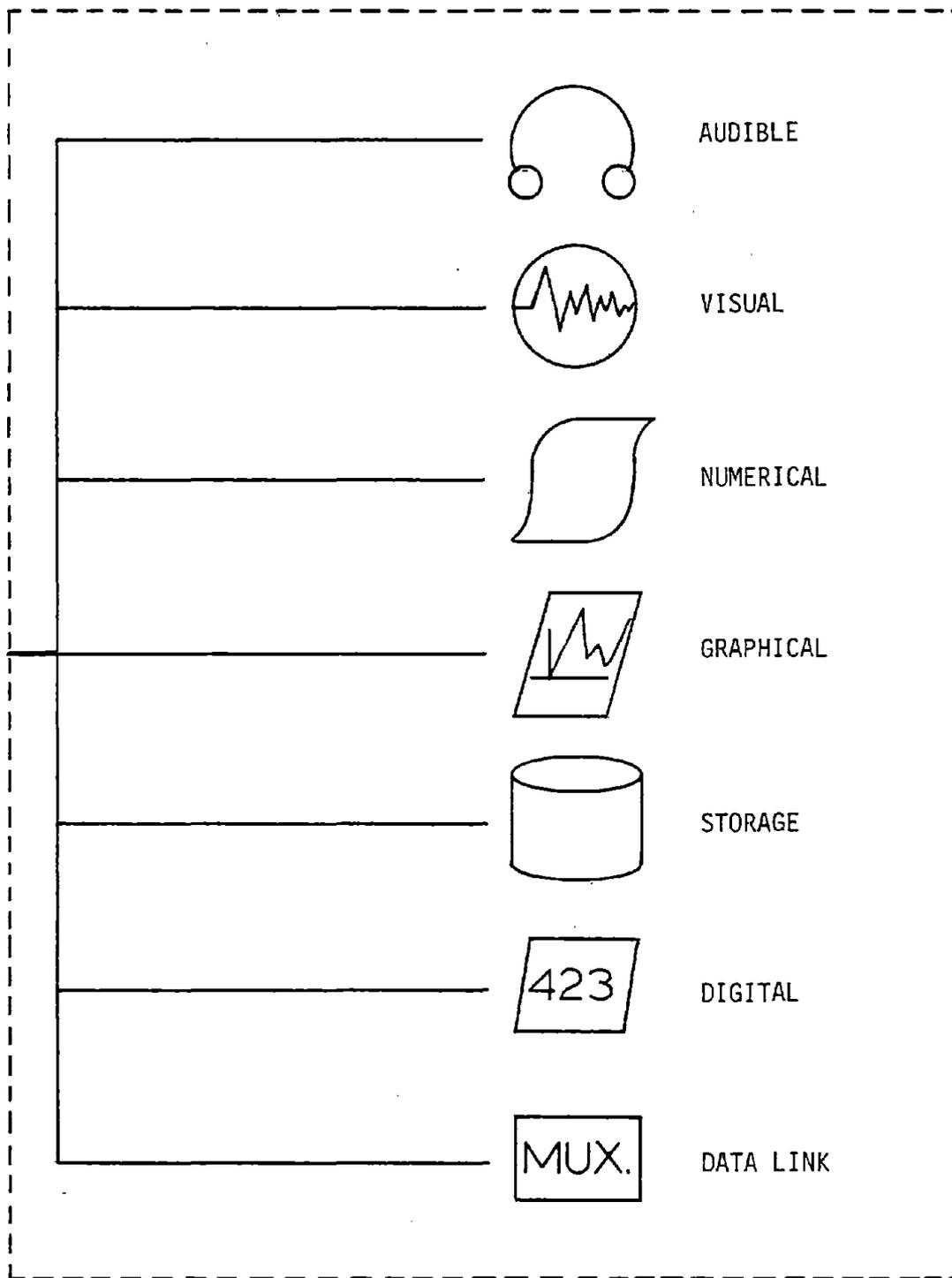
FIGURE 3-4— OUTPUT STAGE OPTIONS

Microseismic Systems

Early microseismic systems were developed and constructed inhouse, but, with widespread usage commercial units became available. Now a number of manufacturers, listed in Appendix C, sell both components and complete microseismic monitoring systems.

Single-Channel Systems

The first, and still available, commercial microseismic monitoring system was the Seismitron, of the Walter Nold Company. This instrument, shown in figure 3-5, consists of a geophone probe containing a crystal transducer and an impedance matching transformer, an amplifier, a headset and a counter. A small meter on the amplifier deflects when an event is detected and is also used as a battery and amplifier operating-level check. An additional output jack is available to record from or display the amplified geophone output.

The Seismitron detects signals in the audio frequency range of 20 - 15,000 Hz but is most sensitive to signals in the 1000 Hz range. A number of other single-channel microseismic or acoustic-emission monitoring units are available. Most of these later units are more sophisticated, having variable frequency response, filtering capabilities, data processing capabilities, and usually some form of printed or hard copy output.

Multi-Geophone Systems

Multi-geophone portable and fixed systems are available for both microseismic and acoustic-emission monitoring. These systems are basically identical to the single-channel system except that up to 8 channels of microseismic data from one or more monitoring locations are obtained simultaneously. Figure 3-6 shows typical multi-geophone monitoring systems.

Source Location Systems

The most sophisticated of the microseismic monitoring systems is the arrival-time source-location system. In the acoustic emission field, source location systems have principally been used to monitor the behavior of highly pressurized steel vessels. In the geotechnical field they have mainly been used to monitor rock bursts.

Initially, rock burst monitoring units were only available in component form, but now complete systems can be purchased. One such system, the Electrolab 250 MP, shown in figure 3-7, is described.

The geophone consists of a 1.0 v/in/sec vertical or horizontal-mounted velocity gage followed by a 60-db gain differential preamplifier. The frequency response of the geophone is
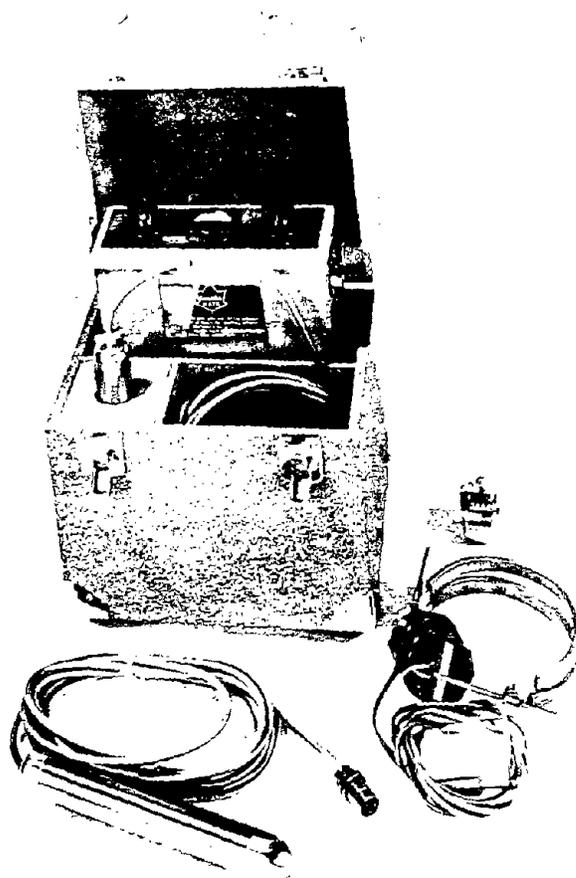
FIGURE 3-5— SEISMITRON PORTABLE MICROSEISMIC MONITORING SYSTEM
(courtesy Walter Nold Co.)

-45-
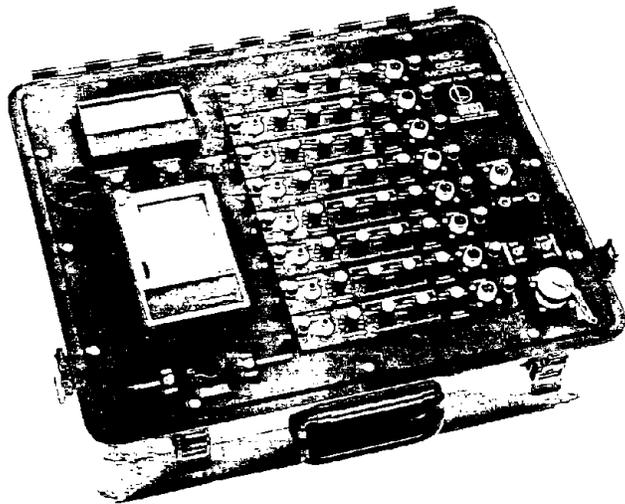
-A- GEOMONITOR MS-2 (courtesy Slope Indicator Co.)
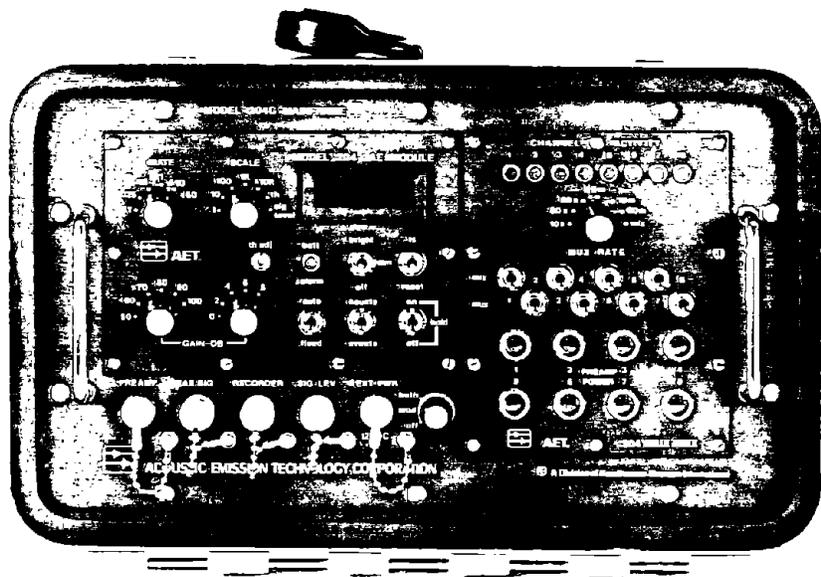
-B- AET-240 (courtesy Acoustic Emission Technology Corp.)

FIGURE 3-6—MULTIGEOPHONE MICROSEISMIC MONITORING SYSTEMS
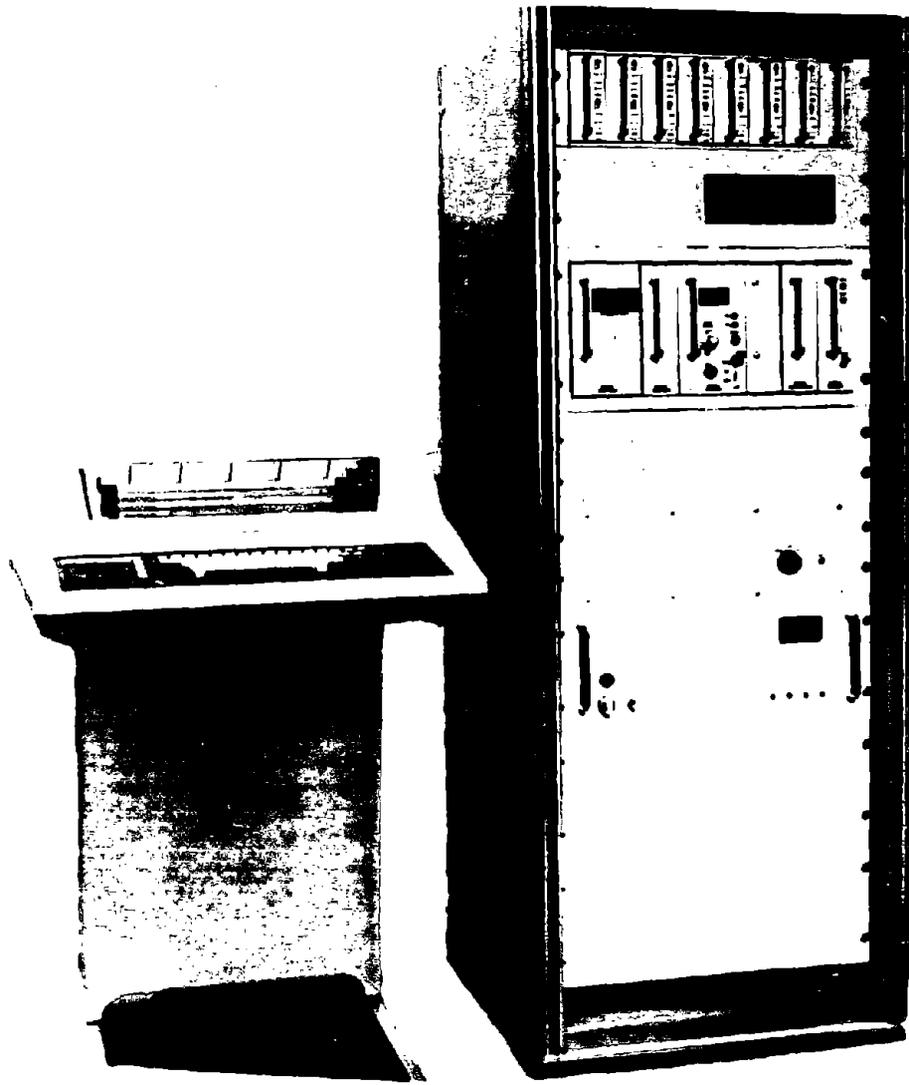
FIGURE 3-7— MICROPROCESSOR ROCK BURST MONITORING SYSTEM
(courtesy Electro-Lab)

flat (±3 db) in the 10 - 2500 Hz range. Four-conductor shielded cable is used to connect the geophone to the data processor or to an underground junction box. Power, 18 to 28 vdc, is supplied to geophones through 1 pair of the four conductors.

The signal conditioning section of the data processing unit consists of a line balancing receiver and a filter interface. The filters cut off all frequencies above 2500 Hz. Adjustable threshold voltage sensors serve as the interface to the micro-processor timing and control section. This section contains an adjustable time window, an event timer with a 50-microsecond arrival time resolution, an energy integrator, and a time of day clock. The calculating section is a high speed arithmetic micro-processor that calculates the source coordinates of detected events. A 50-event storage buffer prevents loss of events during high data rates. The output section contains a high speed printer and/or a data transmission port. Output data is the day, date, time-of-day, geophone and arrival times, energy number, and x, y, z source coordinates of each event. With a time window of 100 milliseconds, up to 9 events per second can be detected and processed.

Short-Period Seismograph

An RBM (rock burst monitoring) system will determine first arrival times, source location and energy number for large seismic events (bumps and bursts) occurring in a mine. However, the amplitude and duration of these events saturates the RBM, causing any number of echo events until the amplitude tails off and finally drops below threshold. In addition, during mine blasting when both blasting events and microseismic events are occurring at high data rates, it is not uncommon to miss small events or get scrambled arrival times for large events. Hence, a short-period seismograph that provides hard copy of all large mine-related seismic events, as well as local and distant earthquakes, is a useful adjunct to an RBM installation. The short-period system can be very helpful in estimating energy levels of bursts and bumps.

A typical short-period seismic system is shown in the block diagram in figure 3-8. The transducer, or seismometer, is usually a highly sensitive velocity gage. The seismometer, shown in figure 3-9, consists of a large mass supported by springs. This mass is centered in stationary coils. Ground motion moves the coils, which are rigidly attached to the case, while the mass tends to remain at rest. Such a seismometer can respond to frequencies in the 1 to 100 Hz range, with a sensitivity in the 16 v/in/sec range. The seismometer should be mounted on a concrete pier poured on bedrock, and can be oriented horizontally or vertically. In most mining operations a vertical orientation is used. A pre-amplifier is usually attached directly to the seismometer and protected from the environment.
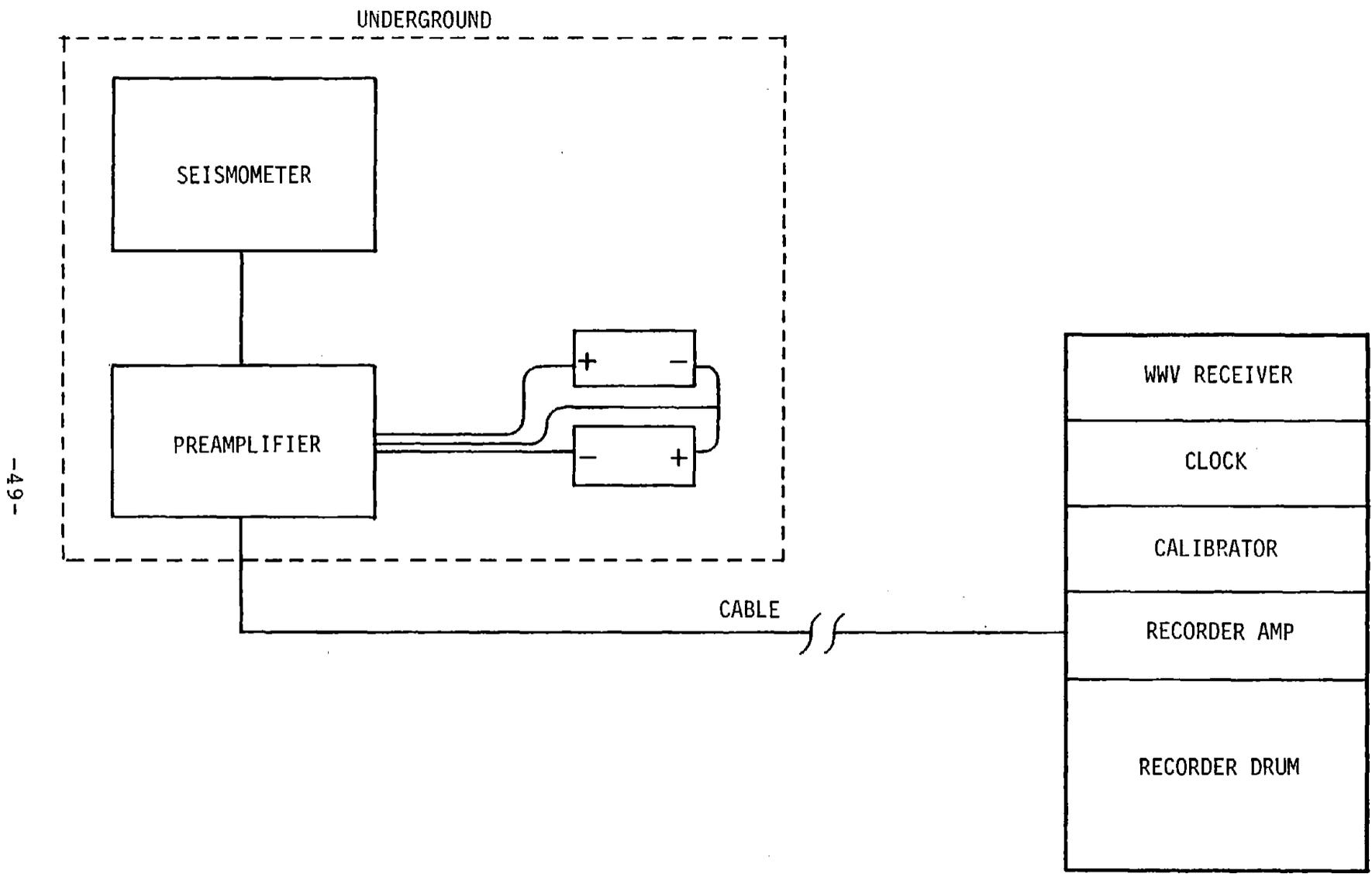
FIGURE 3-8— COMPONENTS OF A SHORT-PERIOD SEISMIC SYSTEM
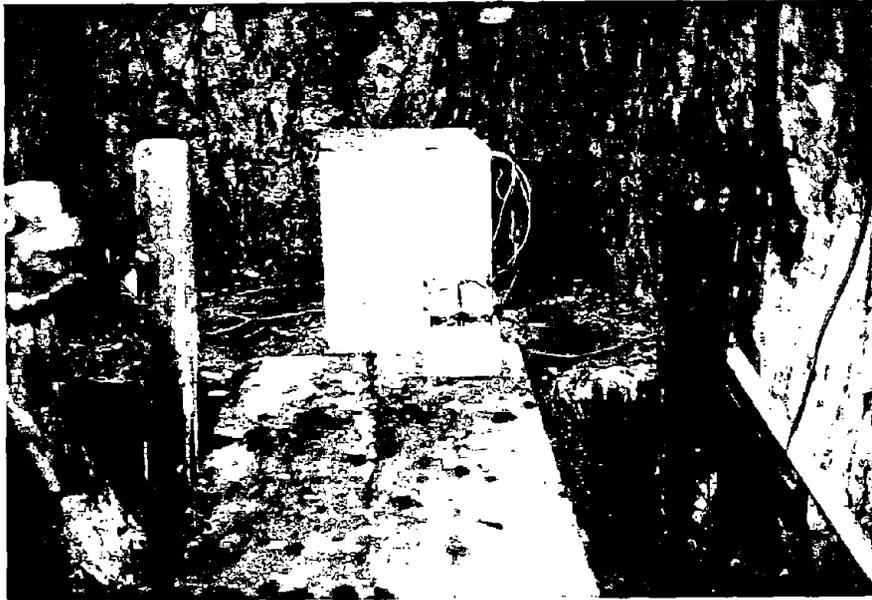
-A- PROTECTIVE COVERING
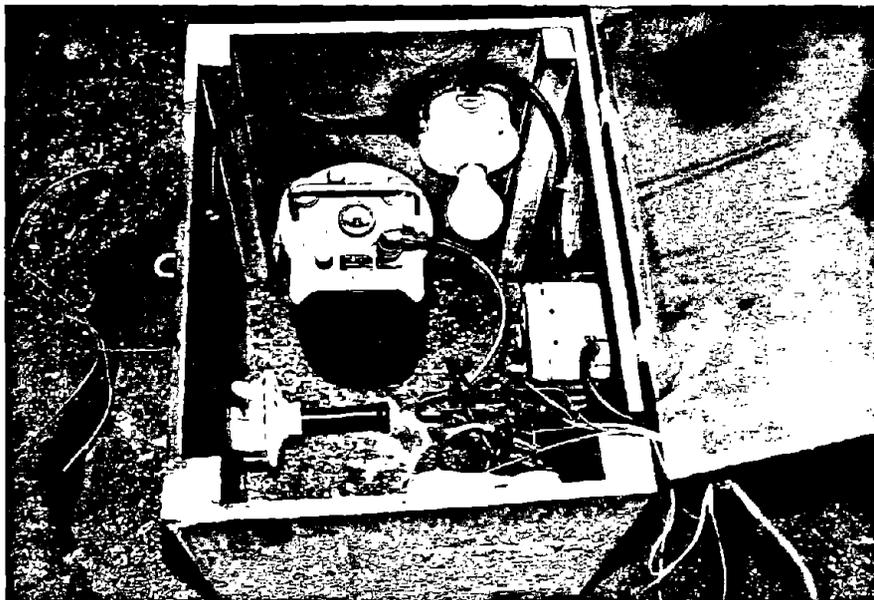
-B- SEISMOMETER

FIGURE 3-9— SHORT-PERIOD SEISMOMETER

The preamplifier has high gain and low noise, with a nominal 4 K ohm impedance to match the critically damped seismometer. The preamplifier has a low or high gain setting, 112 db and 70 db attenuation, respectively, with plug-in or switch-selectable low or high frequency band pass filters.

The frequency response is dependent on the filters, and is usually set from .01 Hz to 10 Hz for U. S. Bureau of Mines short-period seismic monitoring. The seismometer preamplifier is usually battery operated to eliminate ground loops and minimize electrical noise pickup.

The processing part of the system consists of a post amplifier and drum recorder. Heat writing pens are preferred over ink pens to minimize maintenance under mine environmental conditions. A timing system, synchronized with WWV, is used to provide minute, hour, and 24-hour timing marks on the 36-inch removable sheet recording paper. This timing signal is inserted as an electrical signal into the post amplifer so that it appears as part of the recorded signal. Basic controls allow the user to set the recording speed, sensitivity, time-of-day, clock timing mark, amplitude and calibrate the total system. Figure 3-10 shows a picture of a short-period recording system.

A seismogram from a short-period seismic system, with a recorded rock burst, is shown in figure 3-11. A brief discussion on the interpretation of seismograph records for rock burst studies is included in Appendix D.
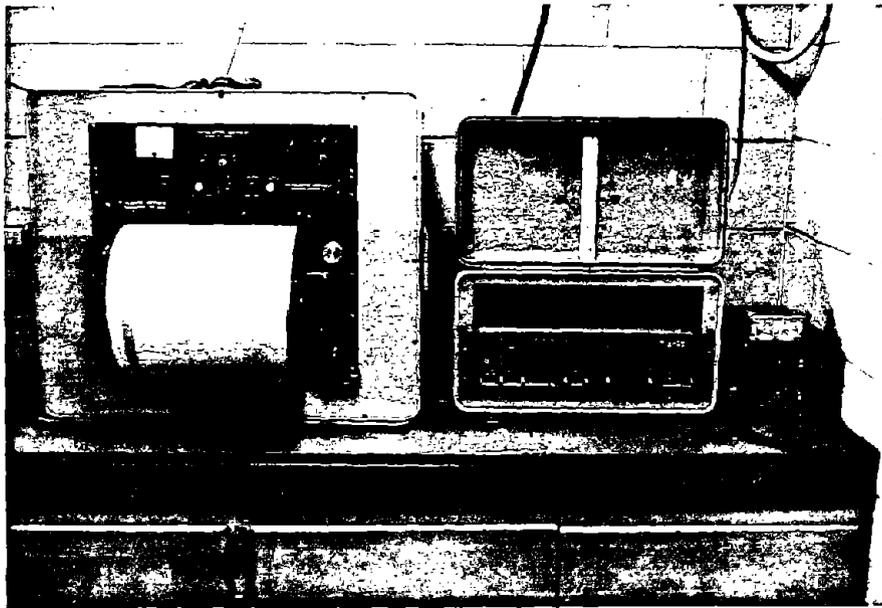
FIGURE 3-10—PROCESSING UNIT AND RECORDING DRUM, SHORT-PERIOD SEISMOMETER
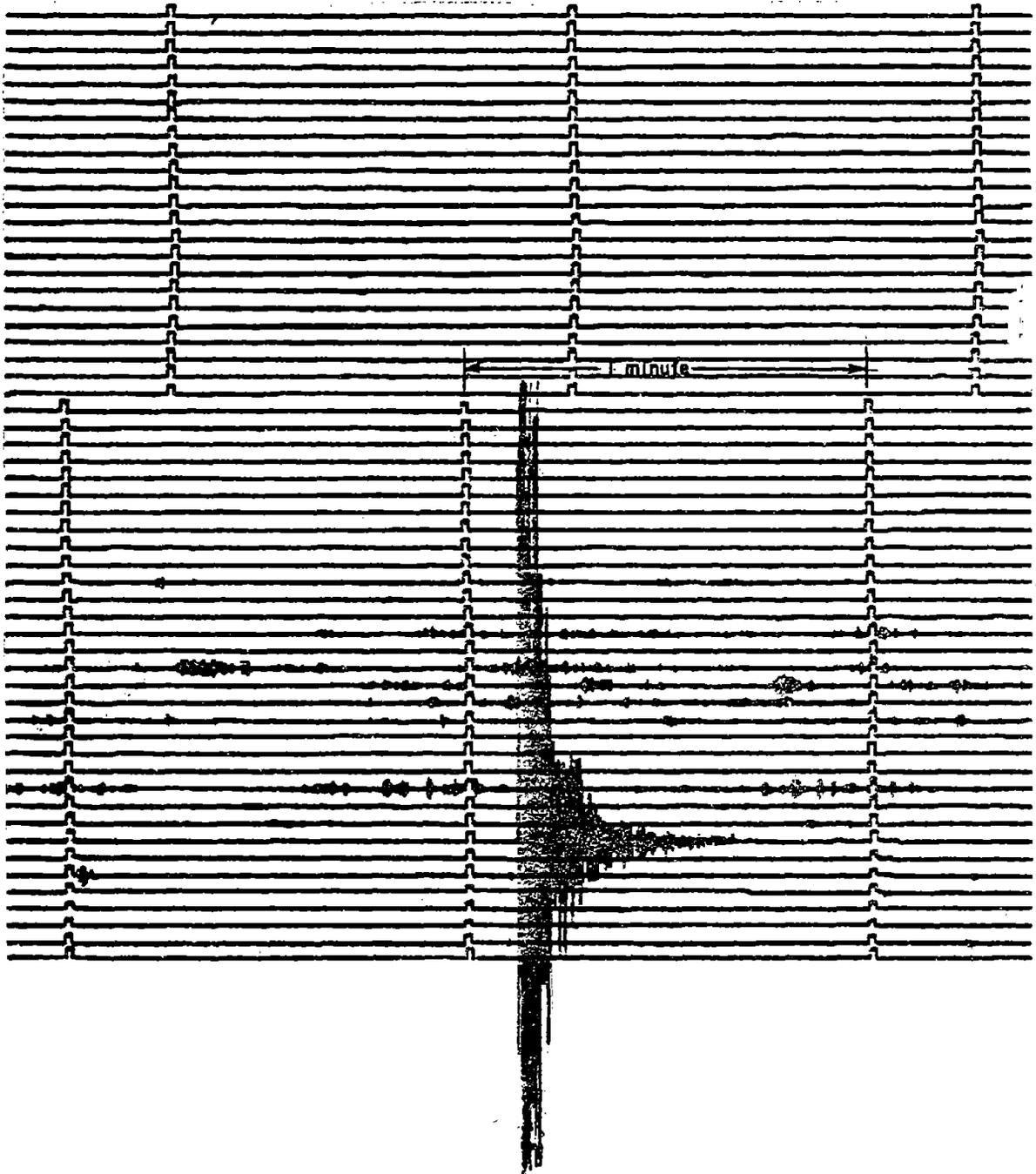
FIGURE 3-11— SEISMOGRAPH RECORD SHOWING A ROCK BURST

CHAPTER 4

DEVELOPING A MICROSEISMIC SYSTEM

The need for microseismic monitoring usually arises from an increase in the occurrence of rock failures that cause hazardous working conditions, damage to equipment and workings, and production delays. Such occurrences, particularly when preceded by audible rock noises, are capable of being detected and recognized at an early stage--usually in sufficient time for the potential failure to be controlled. A number of factors must be considered when developing a microseismic monitoring system. The microseismic components should be matched to the characteristics of the rock noise events generated on site. The mine or site cultural and background noise must be determined so that signal interference problems can be eliminated or minimized. And, the nature of the rock stability problem must be taken into account, as the degree of sophistication of the microseismic system will depend on the severity of the problem. Hence, to determine these factors a test program should be carried out prior to selecting and ordering microseismic components.

Test Program

This test program should determine the following parameters with respect to rock noises being generated on site:

1) frequency range
2) amplitude range
3) attenuation and propagation characteristics
4) seismic velocity characteristics
5) background noise characteristics.

From these data it will be possible to choose the best type of geophone, determine the amount of amplification necessary, the distance a geophone will cover, and whether source locations are possible.

A minimum test program would involve monitoring on site with a portable microseismic unit consisting of two accelerometer pickups, pre-and post amplifiers, a battery-powered storage oscilloscope, and a headset. The procedure is to set up this equipment in potential trouble locations, carry out seismic velocity tests, and observe the detected microseismic events. Both P and S wave seismic velocities are estimated from hammer blow tests, as shown on figure 4-1. The seismic wave from the hammer blow impact triggers the oscilloscope sweep when it reaches the first geophone. Seismic velocities can then be determined from the P and S wave first arrivals at the second geophone, based on the initial deviation of the signal above background. Simple measurements of the oscilloscope trace of an event will establish its frequency and amplitude. Identification of both the P and S
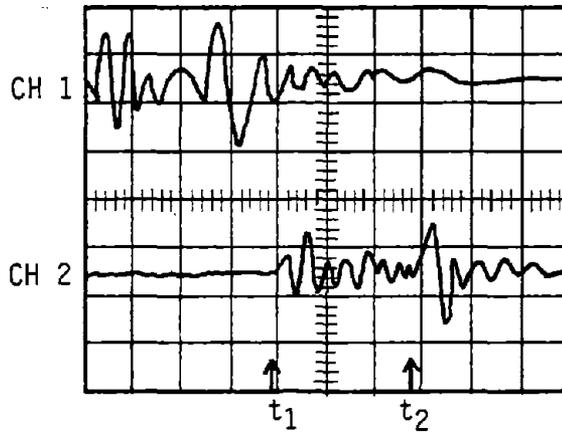
$$t_1 = .0042 \text{ sec} \quad \text{P-wave}$$
$$t_2 = .007 \text{ sec} \quad \text{S-wave}$$
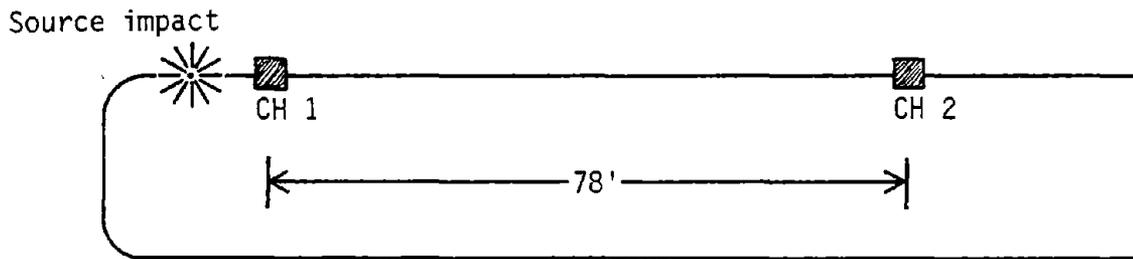
$$V_p = 78 \text{ ft}/0.0042 \text{ sec} = 18,571 \text{ ft/sec}$$
$$V_s = 78 \text{ ft}/0.007 \text{ sec} = 11,143 \text{ ft/sec}$$

FIGURE 4-1— SEISMIC VELOCITY DETERMINATIONS FROM HAMMER BLOW TEST

wave determine the distance the event traveled from source to geophone. Figure 4-2 shows how to determine these parameters from the oscilloscope trace of a detected microseismic event. The attentuation and propagation characteristics of the site can be estimated by carrying out hammer blow tests at various known distances and plotting the resulting frequencies and amplitudes determined for each distance. The advantage of this type of test program is it is cheap and easy to carry out. The disadvantage is that it may take a lot of time to adequately sample enough rock noise events, to provide a required minimum amount of information. These disadvantages are greatly reduced if the field data is recorded on a portable magnetic tape recorder and the tapes are analyzed in the laboratory on the oscilloscope. Background and electrical noise interference would also be noted.

The best, but most expensive and elaborate, test program would use a multichannel monitoring system. This system would consist of both accelerometers and velocity gage transducers, preamplifiers, post amplifiers and a 4 to 7 channel tape recorder. Field testing procedures would be basically indentical except that an array of geophones would be placed in suspected trouble areas. Seismic velocity testing would be done using small explosive blasts as the seismic wave source. The tape recorded data would be analyzed off site using a direct write oscillograph. Preliminary field scans of test blast data should be made to confirm that the blast was recorded on all channels and that all the amplifier gains were set at the proper levels.

From the permanent oscillograph records the frequency, amplitude and distance from source data for each channel would be determined in the same manner as was shown for the oscilloscope traces. Plots of frequency and amplitude versus distance will give the attenuation and propagation characteristics for the site. In addition the data from test blasts can be used to supplement the data from naturally occurring microseismic events. The test blasts will not only give the seismic wave velocities, but can be used to check the accuracy of source locations. Procedures for determining source locations are given in Appendix G, and test blast procedures are discussed in Chapters 5 and 6. Comparison of the same recorded data for an accelerometer and a velocity gage will aid in determining the best type transducer for the site. Again, background and electrical noise characteristics would be noted. This test equipment, if not available, can be rented.

It should be mentioned that in some cases a pre-purchase test program may not be necessary. Where the stability problem is only an occasional small roof fall or pillar failure a portable single channel microseismic monitoring unit would suffice and could be purchased off-the-shelf. For a mine with a rock burst problem, a rock burst monitoring system is required. A list of manufacturers of microseismic components and systems is included in Appendix C.
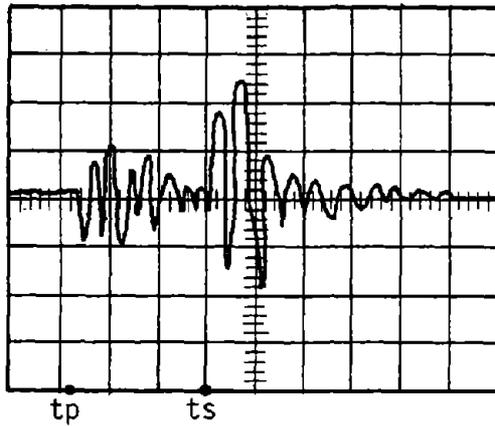
OSCILLOSCOPE CALIBRATION

1 msec/DIVISION SWEEP

1 v /DIVISION SENSITIVITY

tp   ts

FREQUENCY DETERMINATION:

    2 cycles in 1 msec division=2000 Hz

MAGNITUDE DETERMINATION:

    Amplitude ·3.8 DIV X 1v/DIV=3.8v P-P

    Amplifier gain 1000

    Transducer output 3.8v/1000=3.8mv

    Transducer sensitivity 350mv/g

    Signal magnitude 3.8mv/350mv/g=10.8mg

DISTANCE DETERMINATION:

$$\frac{\triangle t \ (s-p)}{1/Vs-1/Vp} = \frac{.004 -.0014}{\frac{1}{11143} - \frac{1}{18571}} = 72 \ ft$$

FIGURE 4-2— DETERMINING MICROSEISMIC WAVE PARAMETERS FROM OSCILLOSCOPE TRACE

Selecting Components

In many cases the stability problem at a particular site is localized and effects only a small area. The rock noises generated will generally be of low magnitude and not detectable outside the immediate unstable area. The problem might be a cracked pillar in a room and pillar mine, a loose roof slab in a mine or a tunnel, an unstable embankment or slope, etc. For these local and isolated problems, which occur sporadically throughout a mine or site, a portable single-channel microseismic unit is generally the best equipment for monitoring.

Single Channel Applications

In selecting components for this type of application the critical consideration is the frequency response of the geophone transducer. For low stress levels and low frequency noises, such as would be expected during slope or embankment failures or movement, a highly sensitive velocity gage would be most effective. Because the frequencies normally generated would not exceed 500 Hz a low frequency velocity gage with a sensitivity in the 2.5 v/in/sec range should be used. It should be pointed out that good results have been obtained using highly sensitive accelerometers attached to steel rods driven into a slope or embankment. Similarly, horizontal drain pipes or cased holes in slopes are also used as wave guides and greatly increase the effective range of accelerometer geophones.

a. The Geophone

For most single-channel applications the best choice of geophone will be a highly sensitive accelerometer--one in the 200 - 500 mv/g range. The frequency response of this gage will be flat or uniform to approximately 5,000 Hz. Though this type geophone has the advantage of detecting rock noise essentially over the entire audio range, it also detects all cultural and background noise in the same range, which can sometimes mask the isolated occurrences of rock noise.

For mining or tunnel construction where the problem is in the near face or heading and mechanical mining is used, the application of conventional microseismic geophones is precluded owing to the continuous, high background noise. In these cases ultrasonic or high frequency geophones have been effective in detecting local failures and potential coal outbursts. The ultrasonic geophone is responsive in the 30,000 - 100,000 Hz range, above the frequency range of equipment generated noise. Because the duration of microseismic waves at these frequencies is very short, any detected microseismic buildup indicates a potential problem in the immediate vicinity of the geophone.

b. The Preamplifier

A preamplifier immediately follows or is attached to the geophone. The preamplifier increases the level of the signal to establish a good signal-to-noise ratio and prevents deterioration of the signal during transmission to the processing part of the system. Preamplifiers are normally set for gains of 40 db or 60 db (amplifications of 100 or 1,000 respectively). For velocity gage transducers the preamplifier can have a low input impedance, but for accelerometers the preamplifier must have a high impedance to provide full output and low-frequency response. For versatility, the preamplifier should have a high impedance so that either type transducer can be used.

c. The Processing Unit

The output from the transducer - preamplifier geophone package is cabled to a small processing unit, consisting of further amplification and output channels to accomodate simultaneous headset listening and recording or counting devices. Some processing units provide signal filtering, event counting, event rate counters and hard copy.

The advantage of single-channel monitoring is that a person can carry a light-weight unit to any location and listen to or record data for a short period of time, making on the spot stability decisions as necessary. An experienced operator can cover a large number of active working areas on a daily basis.

Individually purchased components can be assembled to make a single-channel unit, but a number of manufacturers make ready-to-go single-channel microseismic units that can be tailored to specific monitoring needs.

Multigeophone Applications

When problem areas are numerous, or of large dimensions, or continue as mining progresses, it may be better to establish a number of fixed single-channel monitoring locations that can either be checked at any time or monitored continuously. This reduces the time and sometimes difficulty in getting to underground or surface monitoring locations. The chief advantage is wider coverage and continuous monitoring, which afford much better control in determining the stability of hazardous or unstable areas.

Components for this type of system are identical to the single-channel application except that the geophone outputs are cabled back to a multichannel recording and monitoring unit. Multigeophone processing and control units come with a wide variety of options; hence, a unit can be ordered that best suits a specific site and application.

Problem areas that have been monitored by multigeophone systems include the roofs and walls of large open stopes, roofs and pillars in room and pillar mining, pit walls in open pit mines, cut slopes and slide zones along highways.

The number of geophones required to monitor any particular zone will depend on the size of the area to be monitored and the distances the microseismic wave will propagate and still be detectable. Normally, the rock noises associated with general mine or slope failures cannot be detected more than a few hundred feet from their source in solid rock and at much shorter distances in fractured or loose rock and soils.

Source Location Systems

Microseismic source location systems are generally used where a mine or rock structure is under high loads, and failures are often violent, releasing large amounts of energy. In mines, tunnels or other underground excavations where violent failures have occurred, it is very common to hear loud pops, cracks, thuds and bumps. In such high stress environments, particularly where rock bursting may be a problem, the microseismic events accompanying the mining of openings are generally large enough to propagate some 500 feet, and are thus capable of being detected by a mine-wide array and their source point located.

From the results of the test program and using Appendix A, the best transducer for the application is selected. In general, accelerometers should be used for detailed stope monitoring and velocity gages for minewide monitoring. The most commonly used velocity gage geophones have a sensitivity of some 1.0 v/in/sec and respond to frequencies of 10 - 2,500 Hz. The most commonly used accelerometers have a sensitivity of some 0.350 v/g and a frequency response of from 10 - 5,000 Hz.

With respect to source location accuracy, an array for detailed stope monitoring usually provides source locations to within 10 feet. Minewide monitoring, on the other hand, usually locates microseismic sources to within 40 feet. This latter accuracy is usually sufficient to pinpoint potential problem areas associated with a specific geometric or geologic feature in a particular stope. Detailed stope monitoring usually requires at least 5 geophones surrounding each stope; whereas minewide monitoring may require only 1 or 2 geophones per stope. Thus, the number of geophones for a source location monitoring system depends on the size of the area to be covered, the number of burst prone stopes (critical areas), and the desired source-location accuracy.

Preliminary geophone locations for a source location system are determined by trial and error, considering:

1) location of stopes to be monitored
2) available access openings
3) number of stopes involved
4) desired source location accuracy
5) geophone separations at least equal to the mine level interval or around 300 feet
6) a necessary overall three-dimensional geophone geometry.

Taking these considerations into account trial geophone locations are positioned in access openings on mine level maps in known or potential burst prone areas. This exercise results in a first estimate of the number of geophones needed. (An example is given in a following section of this chapter.)

Initial minewide rock burst monitoring systems had 24 geophones. The trend is to achieve better coverage by use of more geophones. More recent installations have started with 32 geophones, and some old 24-geophone systems are being currently expanded to 32 and 48 geophones. These increases will result in better coverage of existing areas being monitored and allow for new areas to be monitored.

The trial geophone locations are revised to correspond to a 16, 32 or 48-geophone array that will provide the desired monitoring coverage. In this manner the preliminary minewide monitoring geophone array is established.

As previously noted, the preamplifier attached to the geophone should have high input impedance to handle either accelerometer or velocity gage geophones. Use of a 60 db gain preamplifier often eliminates the need for postamplification at the central monitoring facility. Where differential preamplifiers are used with accelerometers, they might have to be operated single ended to achieve lowest internal noise level.

Cabling the geophone/preamplifier output to the central monitoring facility has been and continues to be a problem. For a close, centrally located, monitoring station it is possible to run individual cables from each geophone to the monitoring facility. For a monitoring facility on surface or at an underground shaft station, usually thousands of feet from the geophone, it is necessary to run a trunk line to junction boxes on levels, then individual cables to each geophone on a particular level. In this type of cable arrangement the preamplifiers are powered by a voltage source located in each junction box. When properly wired and grounded, the trunk line and junction box type of cable system introduces no additional electrical noise into the overall monitoring system. Furthermore, cable repairs and maintenance are much easier. However, it should be noted that crosstalk problems have been encountered in trunk lines.

Trunk line cables running from level to level range from 6 to 50 pair, with each pair individually shielded. These are essentially permanent installations and should be of high quality with respect to both installation and cable. An armoured or tough jacketed cable is recommended. Lower quality PVC jacketed cables have been a continual problem in shafts because of vulnerability to falling rocks and running water. Three-conductor shield cable is used for single-ended preamplifiers, whereas four-conductor, with one pair shielded, cable is used with differential pre-amplifiers. The higher the cable quality the less maintenance and repair will be encountered.

Required cable lengths are determined from a cable layout plan. This is made with level maps and vertical sections show-ing trunk line cable pair requirements from level to level and geophone cable requirements on each level. The cables are termi-nated in a junction box inside the monitoring facility.

It should be noted that for surface monitoring networks and for some underground applications it may be both cheaper and easier to transmit the geophone data to the monitoring facility using FM radio telemetry. Off-the-shelf components are available for this type application. The Bureau of Mines Denver Research Center has recently developed a microseismic monitoring source location system for open pits which uses FM telemetry to avoid cable problems associated with bench traffic and sloughing pit walls (1).

The monitoring facility is an important part of the overall system. It must be climate controlled, free of dust, large enough to house all the processing and computing equipment, and have sufficient office space for the workers involved. A good monitoring facility underground is usually located near a shaft station and constructed with concrete block walls and cement floor. The electronics within this facility should be powered by a constant-voltage transformer large enough to handle the normal mine-voltage fluctuations. Power isolation is recom-mended.

The makeup of the data processing unit depends on a number of factors. Signal conditioning (filtering and post amplification) requirements are determined from the field test program. That is, high, low or power line frequencies may need to be eliminated when this interferring noise lies outside the dominant frequency range of the on-site microseismic events. The need for post amplification arises when preamplified signal output voltage is below input voltage specifications of the data processing unit. An energy integrating section should be included. A frequency analysis section might be useful for research purposes, but has not yet been shown to be useful for routine monitoring. Ad-justable threshold levels for each event detector are necessary.

The event or time window must be adjustable and range from milli-seconds up to a full second. Arrival time determinations should be accurate to a minimum 100 microseconds. The day-date-time clock must be accurate and have a battery backup. For microprocessor controlled systems the calculating section may require additional calculating power or a separate microprocessor. An output storage buffer that will handle 50 to 100 events is required. The output section will minimally consist of a keyboard, printer and data transmission port. The degree of sophistication desired in the data processing unit will depend on the size of the overall system, the amount of data generated on a daily basis, rock burst severity, and the hazard posed by potential failures. All data processing units should have power-fail, auto-restart to minimize loss of data during power outages.

Microprocessor based data processing units are much more versatile than the original hardwired units. Changes in front end processing can be made by changing only software in the operating program. However, it should be noted that changing microprocessor software is not simple and straightforward at the present time. An automatic drill suppress routine to eliminate the effects of drilling noise is an example of an addition that could be made to the data processing software to enhance data collection. Finally, the microprocessor based data processing units appear to have an economic advantage over previous hardware or software data processing units.

Traditionally microseismic or rock burst monitoring systems have not provided on-line data analysis beyond source location. The latest generation of rock burst monitoring systems solve this problem by having additional on-line computing to provide real-time data analysis. With such a monitoring system, contin-uously updated plots and stability analyses of the microseismic data from potentially hazardous areas can be displayed on a video terminal or plotter. This permits a continuing, more accurate assessment of the problem areas stability. For small mines with low data rates an arrival-time-only data processing unit might be adequate. For large mines where a large number of geophones are used, a data processing unit with an interactive minicomputer is really necessary.

In summary, selecting components for a microseismic location system involves determining:

1) Whether the geophones should be accelerometers, velocity gages or a mixture of both.

2) Whether a 60 db gain preamplifier will eliminate the need for postamplification.

3) The number of geophones required and their pre-liminary locations.

4) A cable layout plan for cable types and requirements.

5) Postamplification and filtering requirements.

6) The location and design of a central monitoring facility.

7) Data processing unit requirements.

8) The need for further or on-line interactive data analysis.

9) The need for spare components and test equipment.

It should be mentioned that for very large or expansive mines, where a high number of geophones may be required, it would be better to operate two or more satellite arrays with arrival time determination capabilities, hooked into a central operating and analysis computer, than to operate the system as one large array. The satellite array concept becomes economic when cable costs are considered and will provide much better data and control, as there would be little, if any, confusion from events occurring at the same time in different parts of the mine.

It should be noted that for monitoring small structures or laboratory studies (where the rock noise frequencies generated would be expected to be in the 50 KHz range), standard acoustic-emission monitoring instrumentation can be used directly without modification.

Lastly, a very useful adjunct to a rock burst monitoring system is the on-site installation of a short-period seismic system. Besides providing hardcopy of all large seismic events and rock bursts at the immediate site, this system will detect large rock bursts, earthquakes, and micro-earthquake activity over a very broad area. This provides a means to substantiate or refute reported occurrences of rock bursting and to differentiate between rock bursting and nearby earthquake activity.

Example System Development

A case history of a mining company's development of a rock burst monitoring system is presented as an example. The increase in the price of metals in the late 1970's brought about a resumption in production of a previously operating mine. Since some rock bursts had been experienced with the previous mining, mine management decided to explore the possibilities of installing a rock burst monitoring system.

The area to be mined was relatively small as shown on figure 4-3. The daily mining production would be on the order of 250 tons of relatively low grade ore. Combined with an only

SURFACE

0 LEVEL

TUNNEL

200 LEVEL

400 LEVEL

800 LEVEL

1200 LEVEL

SHAFT

SEA LEVEL

2800 LEVEL

3000 LEVEL

3100 LEVEL

3300 LEVEL

3500 LEVEL

3700 LEVEL

3900 LEVEL

4100 LEVEL

4300 LEVEL

E10,000

E13,000

E15,000

MINING
AREA

0   500   1000

FEET
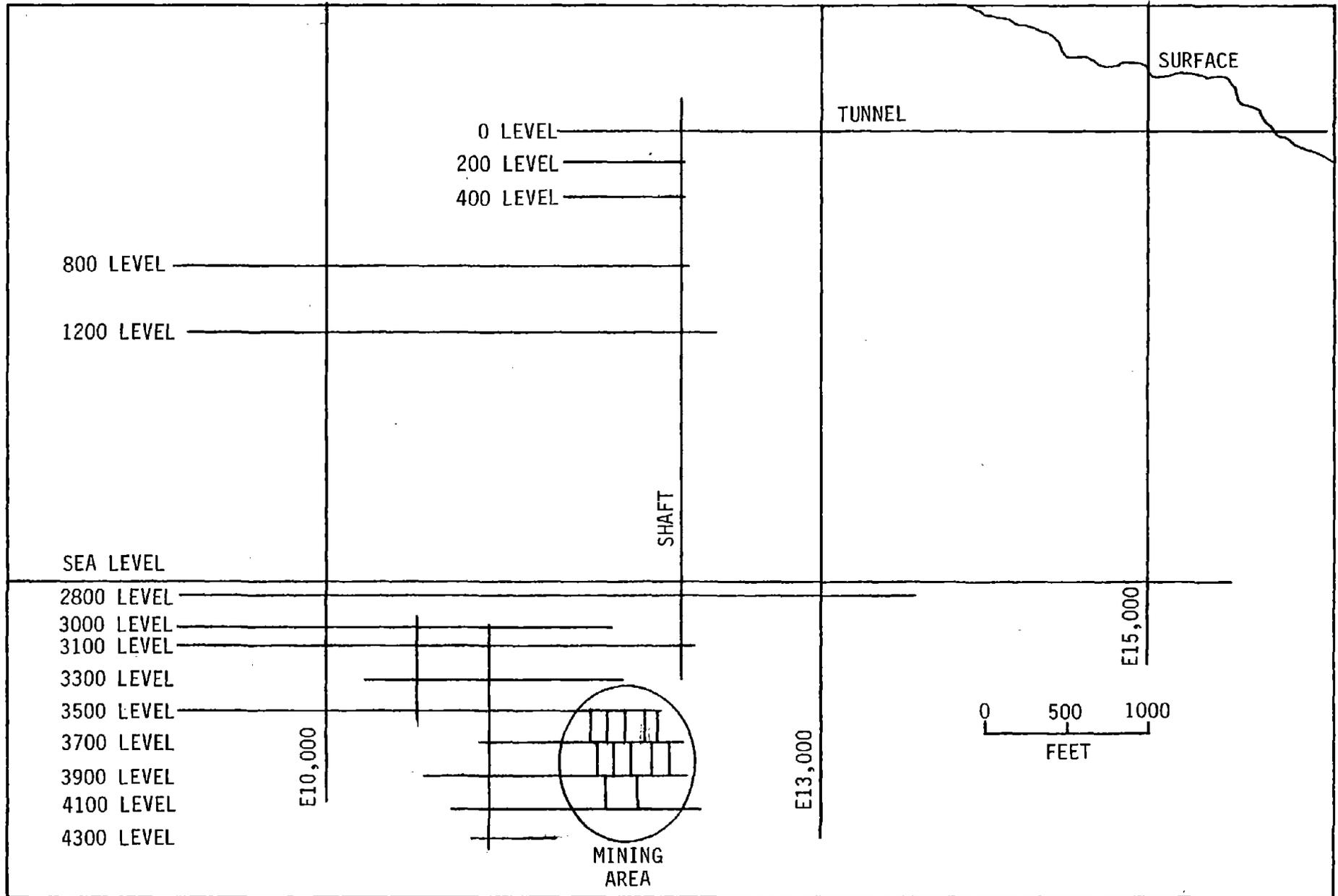
FIGURE 4-3— LONGITUDINAL PROJECTION OF MINING AREA CONSIDERED FOR MONITORING
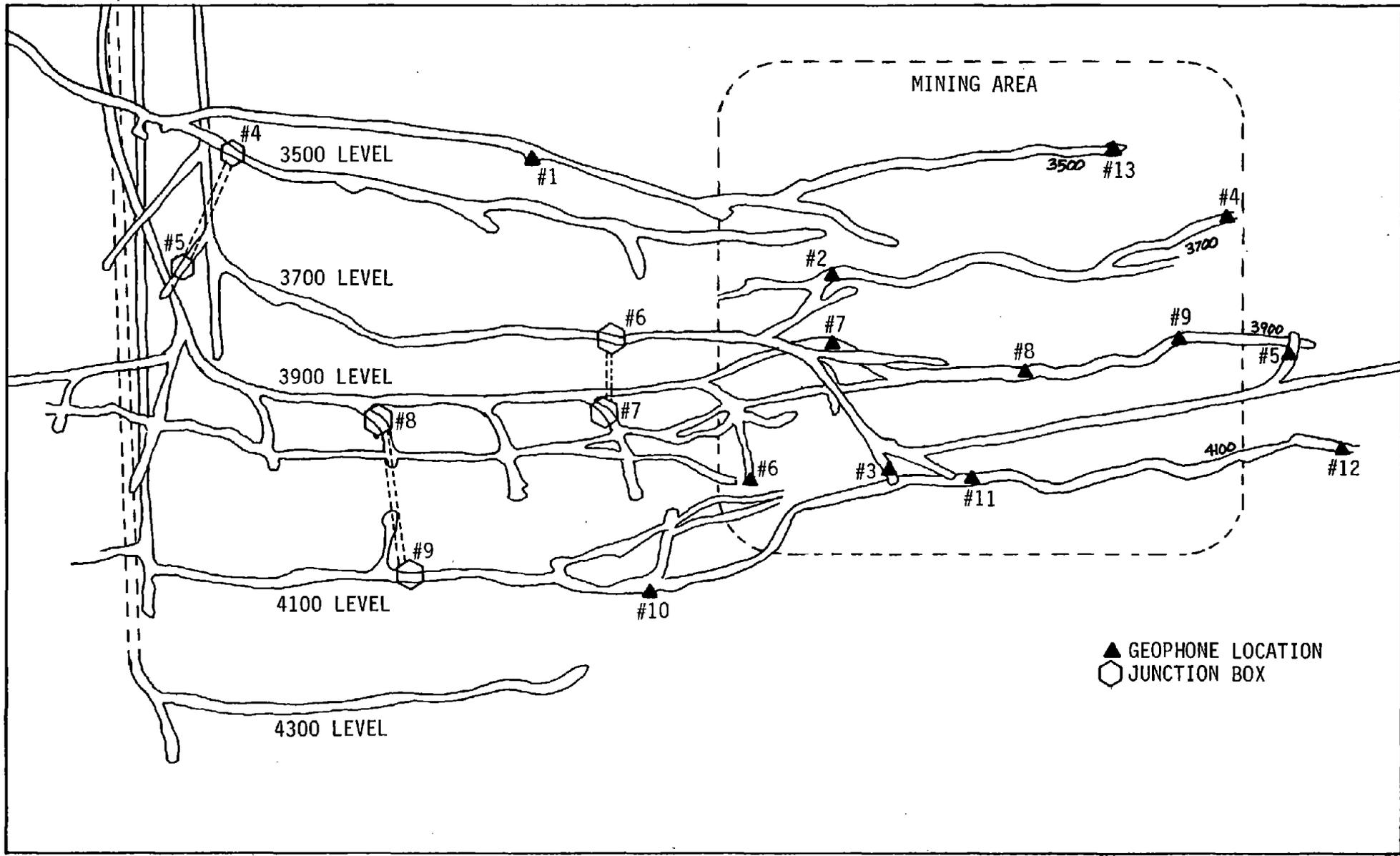
FIGURE 4-4— GEOPHONE ARRAY FOR CURRENT MINING

3100 ▭ RBM ═══ JB 2

3 6-PAIR CABLES

4 CONDUCTOR GEOPHONE CABLES

3300

3500 JB 3 ═══ JB 4   G-1   G-13

3700 JB 5 ═══ JB 6   G-2   G-3   G-4   G-5

3900 JB 8 ═══ JB 7   G-7   G-8   G-9

4100 JB 9   G-10   G-11   G-12
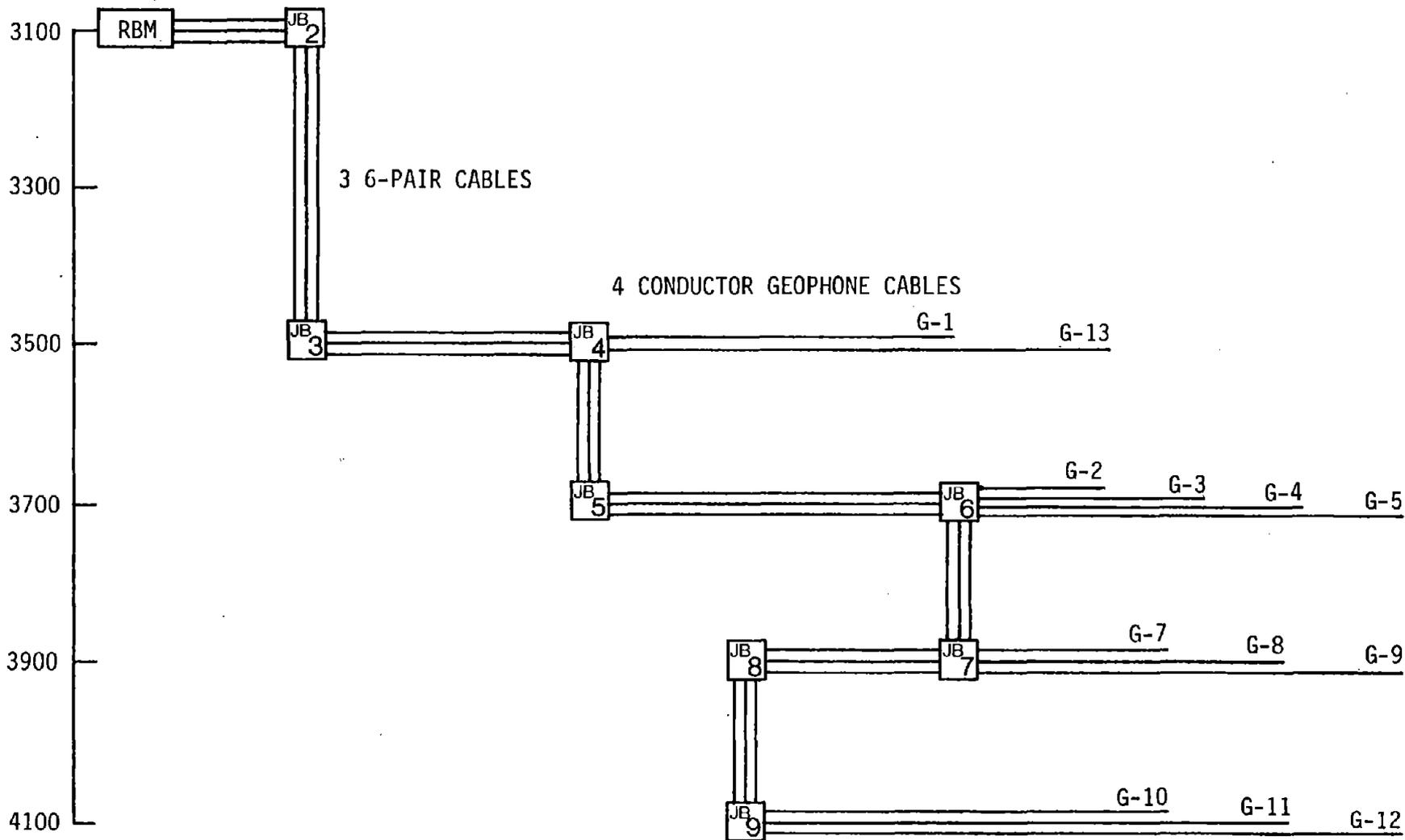
FIGURE 4-5— OVERALL CABLE DIAGRAM

intermittent bursting problem from past mining it was felt that a sophisticated and expensive monitoring system would not be justified. Hence, the guidelines for developing the system were to determine the minimum amount of equipment to produce only the necessary microseismic data at a minimum cost.

Owing to budget restrictions and the fact that a rock burst monitoring system was operating in an adjacent mine, the test program consisted of an underground visit to the mining area to look at both the geology and mining, and to qualitatively assess the level of microseismic activity. The soundness of the quartzite wall rock confirmed the fact that rock bursting could be expected. Discussions with miners indicated that audible microseismic activity was not common except during pillar mining, and past bursting had often been preceded by audible popping, cracking and bumps. As a result of this minimal test program it was decided that a 16-geophone arrival-time-only monitoring system would provide the necessary data within the cost guidelines.

From study of level maps in the mining area a preliminary geophone array was selected. The current mining area could be covered by the 13-geophone array shown on figure 4-4, and future mining would be covered by increasing this array to 16-geophones. For this minewide type array the transducer selected was a velocity gage with a sensitivity of 1.0 v/in/sec and a frequency response in the 10 - 2500 Hz range. To eliminate the need for post amplification 60 db gain differential preamplifiers were chosen.

The best location for the monitoring facility was on the 3100 level near an underground winze hoistroom. This location was close to the underground mine office, which would allow for good communications between monitoring personnel and mine supervisory personnel. The cable network, shown diagrammatically on figure 4-5, would consist of a trunk line of three 6-pair individually shielded cables from the 3100 level down the winze to the 3500 level, then out to the mining area and down escapeway raises to the 3700,3900 and 4100 levels. It was felt that with the three 6-pair cables, as opposed to a single 19-pair cable, there would be part of the system always operating should cable damage occur in the raises and along the levels. Junction boxes were located at the top and bottom of each raise to serve single geophone cables along levels, and to provide for better cable maintenance and trouble-shooting. The junction boxes servicing geophones were equipped with power supplies for the preamplifiers and a light to keep the junction box dry. In addition, the light showed the live voltage connected to each junction box was operating.

Signal conditioning for the data processing unit was to consist of filters to cut off frequencies above 2500 Hz. The processor was to determine day, date, time-of-day and the arrival time differences for the 16 geophones to 50 microseconds. In addition, it should have an energy integrator on one channel so the relative magnitude of an event could be determined. The threshold detectors should be adjustable from 0 - 5.0 volts and the time window adjustable from 50 microseconds to 1 second. An event would be considered legitimate when 5 or more geophones were hit during the time window. If 4 or more geophones were hit during any 50 microsecond time interval the event was to be considered an electrical spike and rejected. The processor must be able to store data from at least 50 events to be able to handle high data rates during mine blasting.

The output stage of the monitoring system was to be a fast printer to allow for fast throughput of the processed data during high data rates. In addition, there should be a parallel output port that will be compatible to send data over a standard data transmission line.

Following discussions with mining companies with operating rock burst monitoring systems and potential equipment manufacturers, a complete rock burst monitoring system was ordered based on the considerations and specifications previously stated.

Ordering a Microseismic System

After the test program and component selection are completed, the microseismic monitoring system is ordered. The initial step in ordering a system is to contact equipment manufacturers to determine what equipment is available and whether it can be modified to suit specific site requirements. In addition to studying the manufacturers' literature and specifications, one should contact their representatives directly about their products' suitability for a particular application. Manufacturers should be asked about their system's performance, warranty, service, installation help, manuals, etc.

The second step, particularly with respect to mine applications, is to contact other mines or construction companies having operating monitoring systems about their experiences with both equipment and procedures. Government and/or university research organizations involved in microseismic and acoustic emission research and equipment development also should be contacted. A list of such organizations, including mines operating microseismic location systems, is included in Appendix E.

The third step in ordering a monitoring system is to assemble all information from the test program, from equipment manufacturers, from monitoring system operators, and from researchers or experts in the field and then develop final specifications. These specifications will include:

1) Type, number and transducer characteristics,
2) Type, number and preamplifier characteristics,
3) Types and lengths of cables, including junction boxes and power supplies,
4) Characteristics of data processing unit,
   a. Signal conditioning section
   b. Processing section
   c. Output section,
5) Characteristics of additional data processing requirements.

The normal procedure is to then send the specifications to suitable equipment manufacturers with a request-for-quote. It should be noted that components for early rock burst monitoring systems were not available from any single manufacturer, hence all components were ordered separately and then assembled. Though this may result in the best possible combination, the interfacing of components can be very difficult and beyond the purchaser's capabilities. It is recommended that monitoring systems, and particularly source location monitoring systems, be purchased from a single source so that, in effect, a complete system can be installed.

The final step is placing the order with the manufacturer or manufacturers selected on the basis of their quotes, delivery dates, past performances, warranty and service, and installation assistance.

References

1. Lepper, M.C., Poland, A.P., and C. T. Mullis. A Microseismic System for Monitoring Slope Stability. Bu Mines RI 8641, 1982, 64 pp.

CHAPTER 5

INSTALLING A MICROSEISMIC SYSTEM

A strong effort is required in the physical and electrical installation of microseismic equipment. Good planning will minimize both installation and future maintenance problems.

Physical Considerations

Microseismic monitoring systems for geotechnical applications must function in a hostile environment -- hostile with respect to temperature, humidity, and risk of physical damage.

Geophones

The mounting of geophones is not difficult but does require care. The geophone must be well bonded to solid rock and protected from damage and may have to be shielded from mine or cultural air noise. This requirement applies to portable single-channel monitoring as well as fixed geophone arrays.

General geophone locations for multi-channel systems are usually selected during the system development stage so the number of geophones and cable requirements can be determined. Specific geophone locations cannot be assigned until the general locations are inspected and solid rock is found. This inspection usually involves finding apparently solid rock, then tapping the rock surface with a hammer or bar. Solid, intact rock will emit a ringing sound; whereas broken, fractured or detached rock will usually produce a thud of lower frequency. At most underground locations, solid rock can be found at the surface of the opening. A short, 1 to 2-ft hole of 2½ to 3 inches in diameter is recommended. For vertically oriented transducers, the hole is drilled up into the back, and for horizontally oriented transducers, the hole is drilled into the wall or rib. This hole should be within 5° of the desired orientation and placed out of the way of present and future mine services--pipes, cables, fan lines, etc. So the geophone can be recovered later, a plastic block is usually bonded to the end of the hole with a quick-set cement. The plastic block should have a threaded hole into which the geophone can be screwed and tightened to achieve good coupling. It should be noted that in access openings no longer in use a hole may not be required--the plastic block can simply be cemented to a fresh rock surface. Figure 5-1 shows typical underground surface mounting procedures.

Where solid rock cannot be found, a hole some 10 to 30 feet in depth may be required to get beyond the fractured or loose rock zone (1). Mounting procedures are essentially the same, except the hole size may have to be a little larger, if possible, and special mounting tools fabricated for attaching the plastic block and screwing in the geophone. Where geophones must be placed in long drill holes, it is usually necessary to make up

-A- VERTICAL MOUNT   -B- HORIZONTAL MOUNT

ACRYLIC PLASTIC
DISC TAPPED
FOR 3/8" NC SCREW ─────   HYDROSTONE
                                  CEMENT

BORE HOLE TO ─────
CLEAR 1 3/4"

SHRINK-TUBING OR ─────
TAPE INSULATION
FOR WET HOLES

                                  FOAM RUBBER
                                  NOISE SUPPRESSANT

MOUNTING ANGLE
LESS THAN 5°
FROM VERTICAL
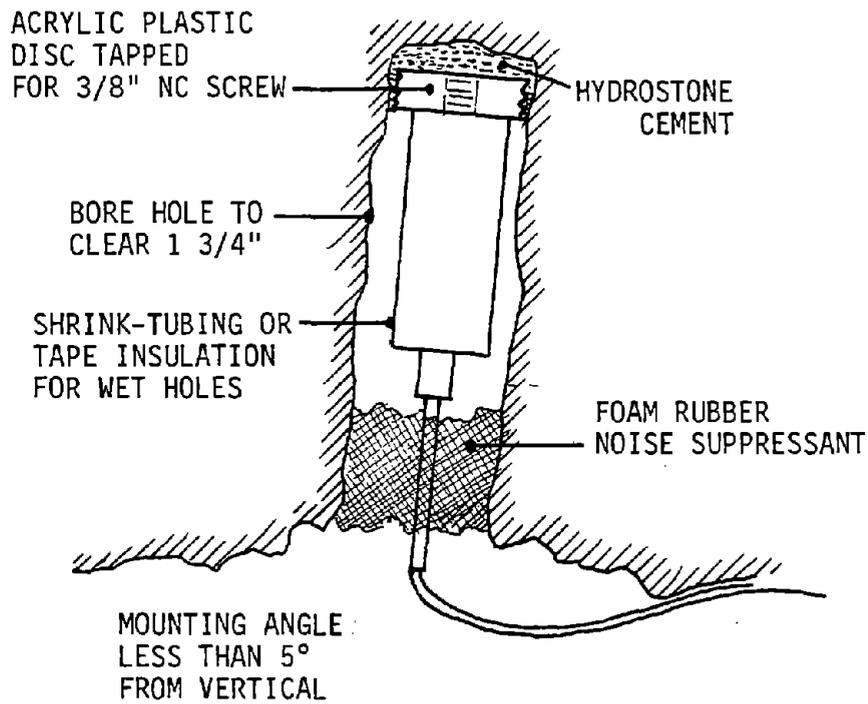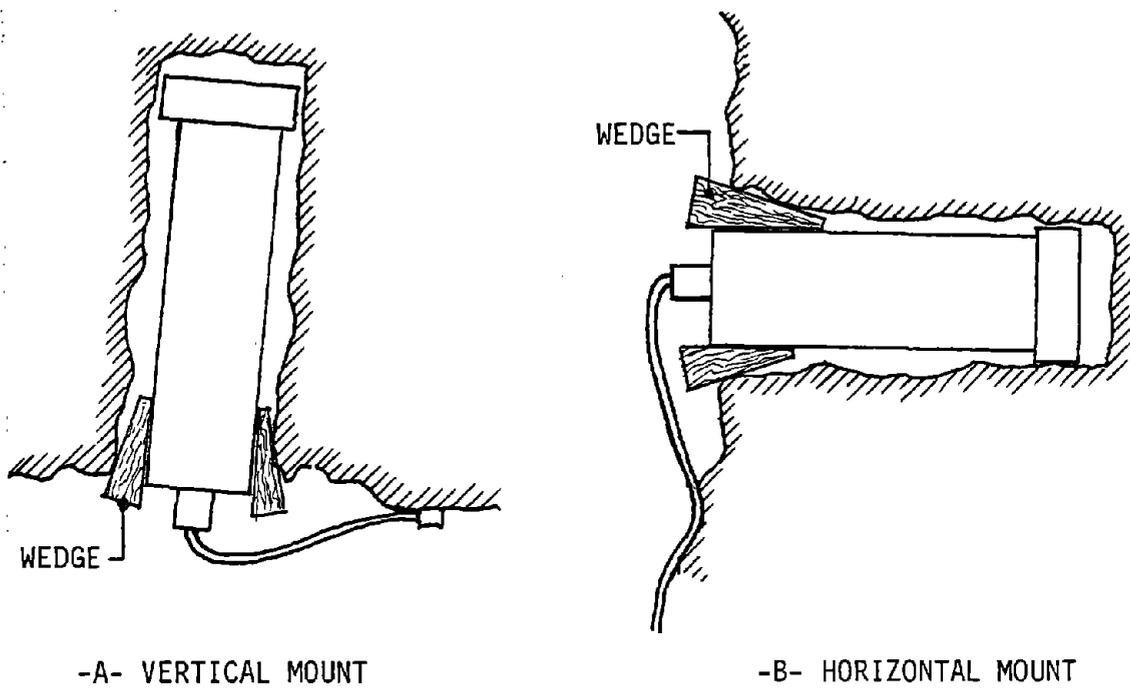
FIGURE 5-1— UNDERGROUND GEOPHONE MOUNTING PROCEDURES

a special geophone assembly that can be affixed to any depth. Figure 5-2 shows such a deep-hole geophone arrangement. It should be mentioned that in a number of instances deep holes have been utilized by mounting only a shielded velocity gage in a cylindrical plastic block with a sliding wedge arrangement, as shown on figure 5-3. The gage is pushed back into the hole to the desired depth, and the wire-line attached to the wedge is pulled to secure the gage in the hole. In this case, the preamplifier is wired to the gage with leads and mounted outside the hole. However, having the transducer and preamplifier mounted separately is not good practice. The result is a weak physical link, potential moisture problem, and source of electrical noise.

For surface monitoring where it may not be possible to drill holes to reach bedrock, wave guides have been used to get deeper penetration. A wave guide can be a rebar section driven into the soil mass, a horizontal drain pipe, or cased well hole. The geophone is attached to the wave guide, and sounds within the rock or soil mass are transmitted back along the wave guide to the geophone.

Geophone locations must be surveyed to the nearest foot, and the geophone array must surround the study area in all dimensions if microseismic sources are to be accurately located.

Cables

The placement of both geophone and trunkline multipair cable is always a problem in any microseismic monitoring system installation. This is particularly true underground where space is limited, alternate cable routes are not available, and the cable, wherever placed, is in the way and frequently damaged or cut.

The best procedure underground is to run the microseismic cables separately from mine cables and away from mine services (water lines, compressed air lines, ventilation lines, etc.). When this is not possible, the microseismic cables may be run in trays with mine cables or available light lines, subject to safety regulations. In areas of falling rock, such as shafts, raises or boreholes, the cable or cables should be protected by conduit or plastic pipe. Cable runs down shafts should also be supported by cable hangers or a messenger to prevent stretching. Figure 5-4 shows proper underground cable hanging.

Junction boxes servicing microseismic geophone cables should also be out of the way; in a dry location; large enough to provide plenty of room for terminal strips, power supply and a heating element; and should be readily accessible for service work. Terminal strips should be of a high quality plastic, not bakelite which absorbs moisture and expands.
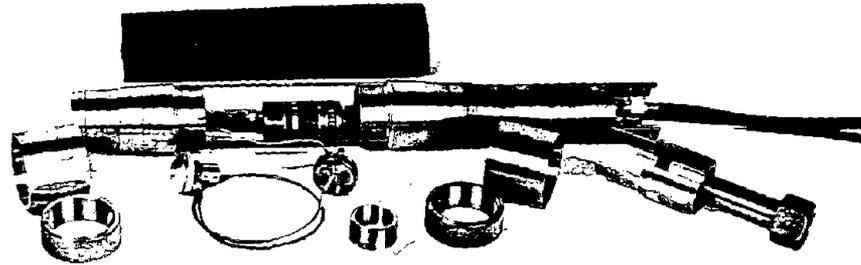
-A- EXPLODED VIEW

-B- ASSEMBLED VIEW

FIGURE 5-2— DEEP HOLE ACCELEROMETER GEOPHONE
(courtesy Kim & Hardy, Penn St. University)

SOLID ACRYLIC PLASTIC CYLINDER-2" DIAMETER

STEEL CABLE

EPOXY →

SLIDING WEDGE

HORIZONTAL
VELOCITY
GAGE
TRANSDUCER

HOLE FOR
POSITIONING RODS

EPOXY

1 PR. SHIELDED CABLE

6"
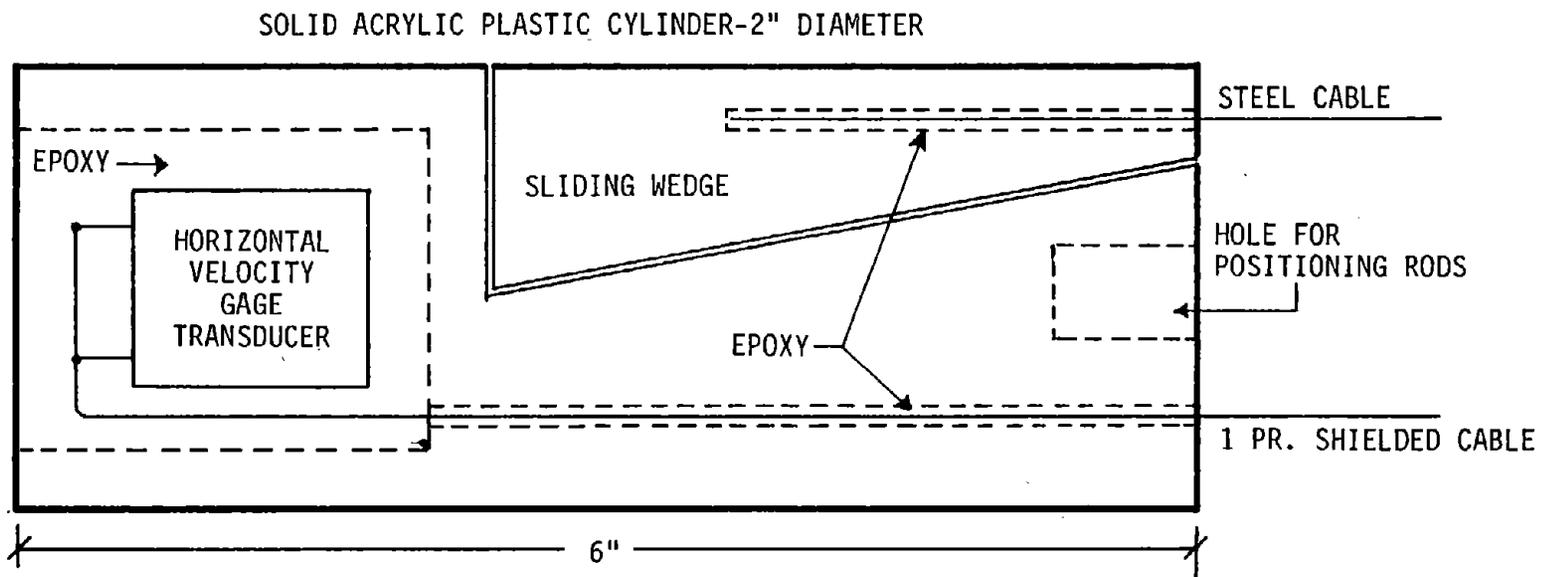
FIGURE 5-3— WEDGE BLOCK BOREHOLE PROBE FOR SHALLOW HOLES

-A- SHAFT

CABLE HANGER EVERY 50 FT.

ROCK BOLT PLATE

TIE WRAP

WIRE
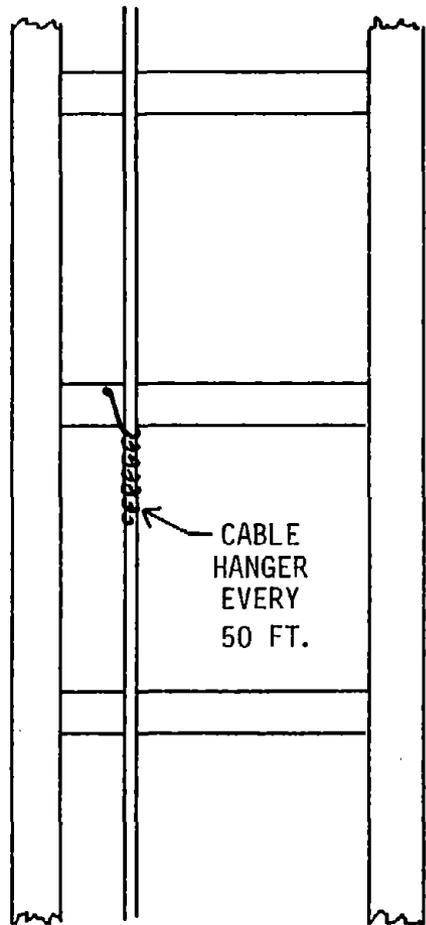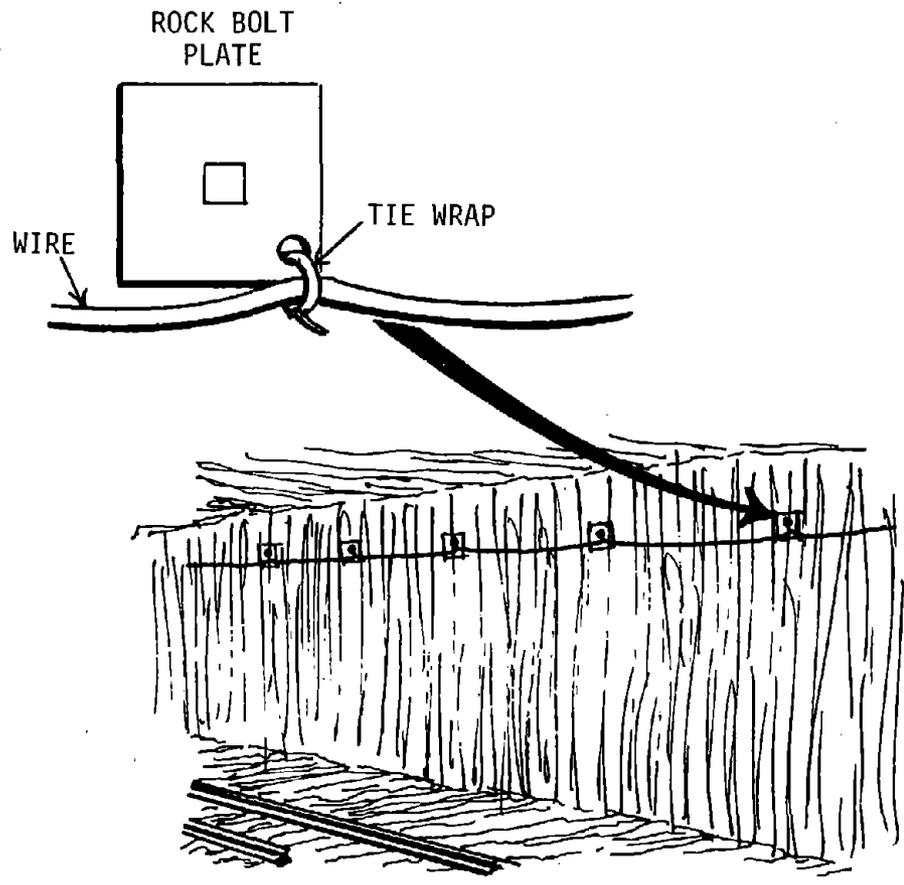
-B- DRIFT

FIGURE 5-4— UNDERGROUND CABLE HANGING

From a physical point of view, single geophone lines connected to a junction box and a multipair line from there to the instrumentation station constitute an easier and neater installation than do single geophone lines all the way to the data processor. This is particularly true when several distant and widely separated mining areas are monitored by a large number of geophones on more than three mine levels.

Any surface monitoring instrumentation or facility should be protected from lightning discharges. To avoid cable problems in monitoring open pit mines, the Bureau of Mines' Denver Research Center has developed a wireless source location system (2). Such a wireless monitoring system would also have application in many underground mines, even with its "line of sight" limitations.

Instrumentation Station

The instrumentation station may be located underground or on surface. In most large and/or deep mines the workings are at some distance from the shaft or surface access, and it is more convenient and cheaper to place the instrumentation station underground. This facility, wherever located, must provide an environmentally controlled atmosphere for the electronic equipment. This is usually done with an air conditioner, a dehumidifier and special electrostatic filtering when necessary.

Most underground instrumentation stations are located near a main intake air shaft for both access and ventilation purposes. This also provides a more visible and direct link to mine management.

Any instrumentation facility should be well constructed and large enough to provide for the data processing unit and output equipment, test and maintenance equipment and work space, a short period seismic system readout, an on-line minicomputer and associated output devices, office space, and storage space. Typically, an underground facility would have some 300 - 400 square feet of space. All instrumentation facilities should be connected to both surface and underground telephone systems to provide immediate notification of hazardous conditions. In some cases separate dedicated communication lines to hazardous areas have been installed. Underground and surface instrumentation stations are shown in figures 5-5 and 5-6.

Electrical Considerations

The major problem in any microseismic installation is eliminating or minimizing electrical noise. This is particularly true underground, where the environment is often wet or humid, extraneous electrical voltages and currents are commonplace, multiple or leaky earth grounds are usual, and geophone transmission to the data processor covers long distances.
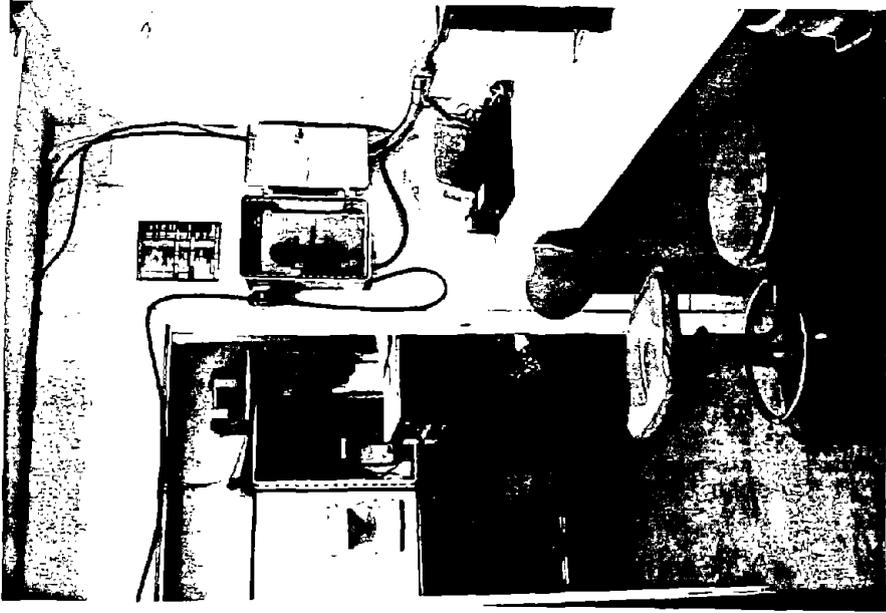
-B- INSIDE VIEW

-A- OUTSIDE VIEW

FIGURE 5-5— UNDERGROUND INSTRUMENTATION STATION

-A- OUTSIDE VIEW

-B- INSIDE VIEW

FIGURE 5-6— SURFACE INSTRUMENTATION SYSTEM

To overcome electrical noise problems, all components of a microseismic system must be electrically compatible and properly wired and connected. This is not usually much of a problem with nonsource location systems, which have few components and small arrays of geophones close to the processor. However, it is a problem with source location systems, where 16 to 48 channels are involved and transmission distances are typically in miles. When cable runs are a few thousand feet or less and the geophones are located on only a couple of levels, individual cables are commonly used between each geophone and the instrumentation station. The individual geophone cable should be 3-conductor shielded for single-ended preamplifier systems, and 4-conductor, 1 pair shielded, for differential preamplifier systems. A central power supply at the instrumentation station provides power back to the preamplifiers through the cable. As was noted in an earlier chapter and explained in Appendix B, the differential system is much less susceptible to electrical noise problems than is the single-ended system. Electrical connections for both type systems are shown in figure 5-7.

Where geophones are spread out on more than 2 levels and the instrumentation station is a long distance away, such as on surface or near an underground hoist room, a system of junction boxes and multipair trunk line cables for transmitting signals is much more convenient. With proper wiring, this technique introduces neither additional noise nor crosstalk between pairs. However, it should be noted that some microseismic installations using accelerometer transducers have had noise and crosstalk problems with multipair trunk lines. Junction boxes make it more convenient to trouble shoot wiring problems and find cable faults. Furthermore, the junction boxes provide a good secondary communications network for the area covered by the geophone array. An overall cable network for a multi-level geophone array is shown in figure 5-8.

On individual levels smaller multipair trunk line cables are run from the mainline or shaft junction box out to another junction box near the geophone arrays. Here, the individual geophone cables are connected to the trunkline pairs in the junction box and power is supplied to the geophones. Figure 5-9 shows the wiring diagram for a single-ended preamplifier system using 3-conductor cables, and figure 5-10 shows the wiring diagram for a differential preamplifier system using 4-conductor cables. The preamplifier power hookup for each geophone is also shown.

The junction boxes should not be electrically connected to the cable shields, as this might introduce grounding noise. All electrical connections should be within the junction box with spade-lug connectors on high quality plastic terminal strips with screw-down connections. A few inches of each amplifier output cable can be left unshielded within the junction box. All shields and bleeder wires must be connected, carried through the junction box, and maintained separately for each pair. The geophone and

TRUNK LINE
CABLE

GEOPHONE
CABLE

○ CH. 1

CHASSIS GROUND
○ CH. 2
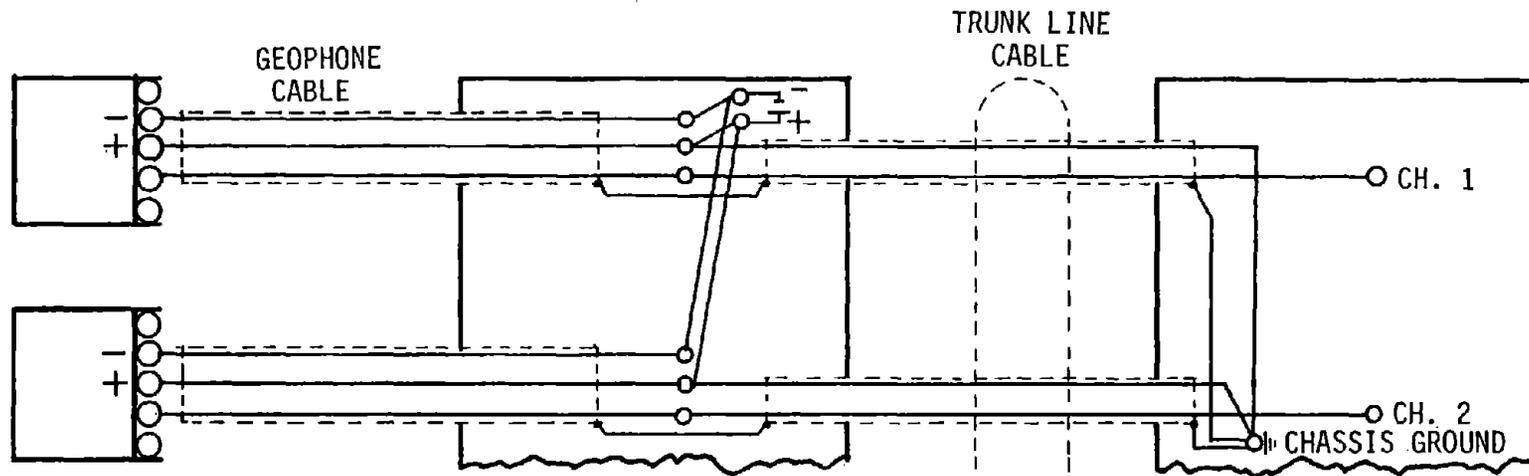
-A- SINGLE-ENDED UNBALANCED SYSTEM

CH. 1

SYSTEM
GROUND

CH. 2
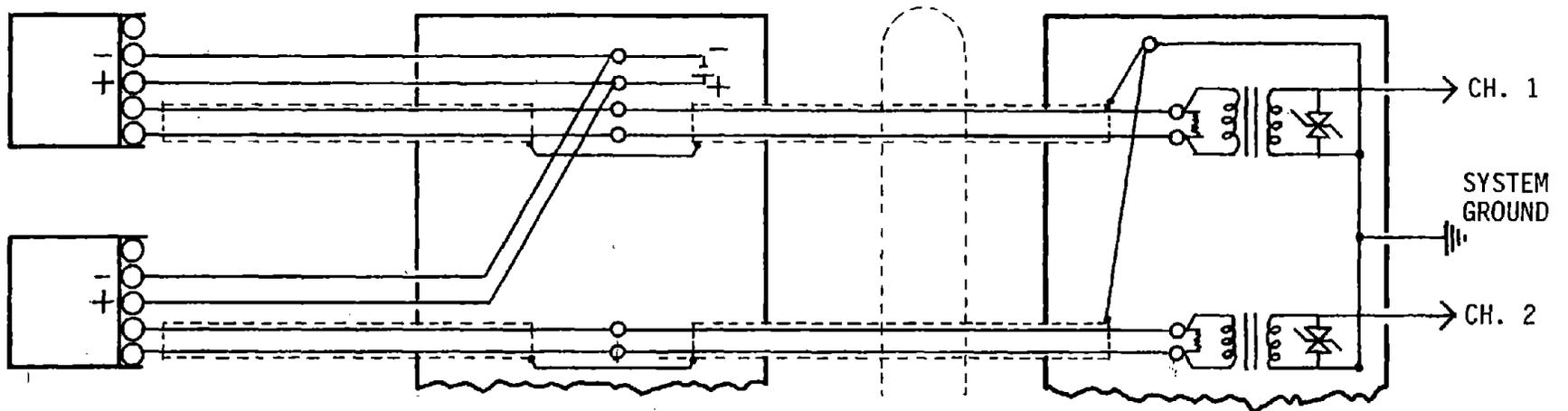
-B- BALANCED SYSTEM

FIGURE 5-7— ELECTRICAL CONNECTIONS FOR MONITORING SYSTEMS

MONITORING
STATION

27-pr CABLE

2000 LEVEL

J-BOX 2900 LEVEL

J-BOX 4500 LEVEL

J-BOX 5700 LEVEL

J-BOX 6900 LEVEL

J-BOX

6-pr CABLE
7300 LEVEL

27-pr CABLE

J-BOX

6-pr CABLE

J-BOX 7500 LEVEL

GEOPHONE CABLES

J-BOX

6-pr CABLE
7700 LEVEL

J-BOX

6-pr CABLE
7900 LEVEL
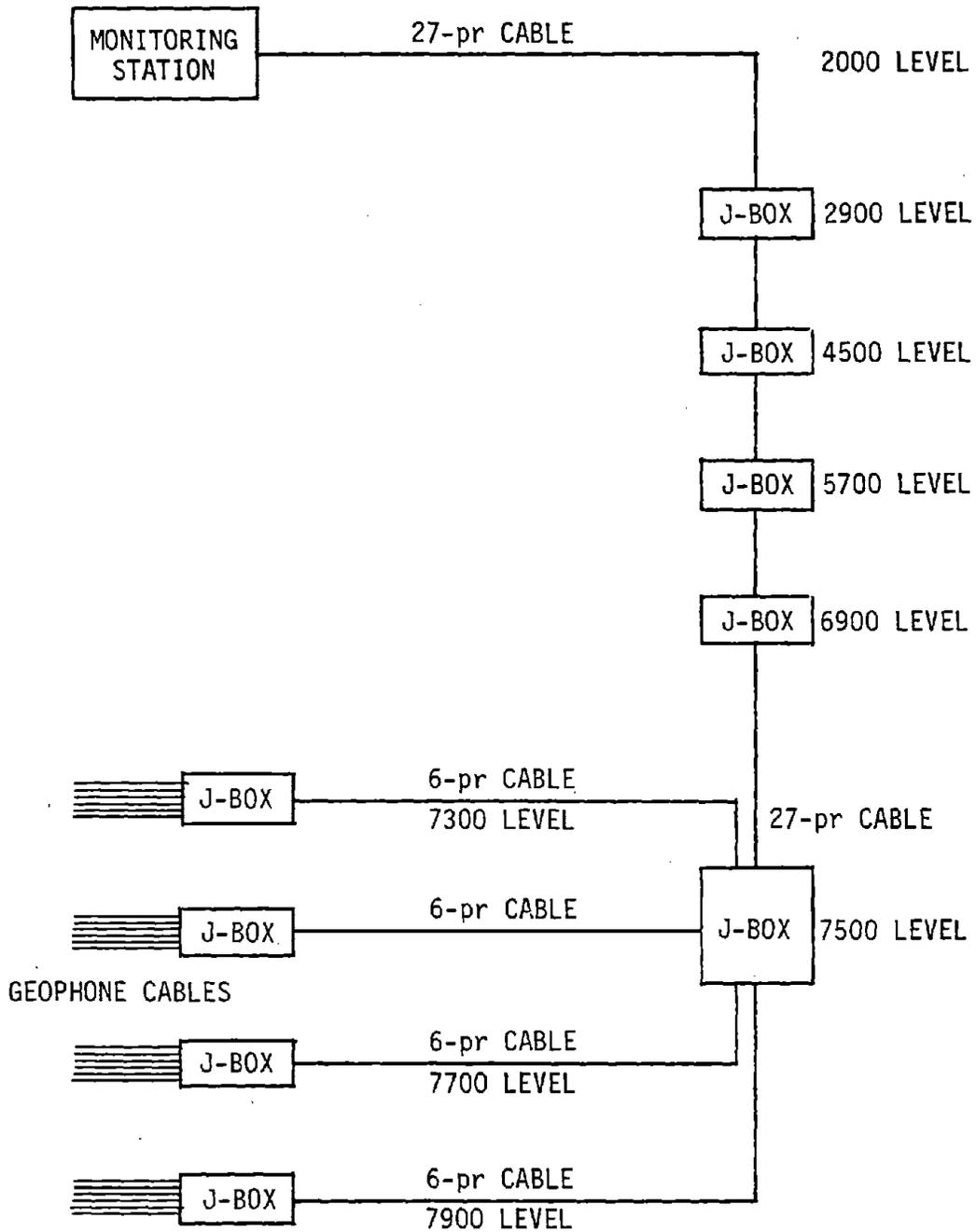
FIGURE 5-8— CABLE NETWORK DIAGRAM FOR UNDERGROUND MONITORING SYSTEM
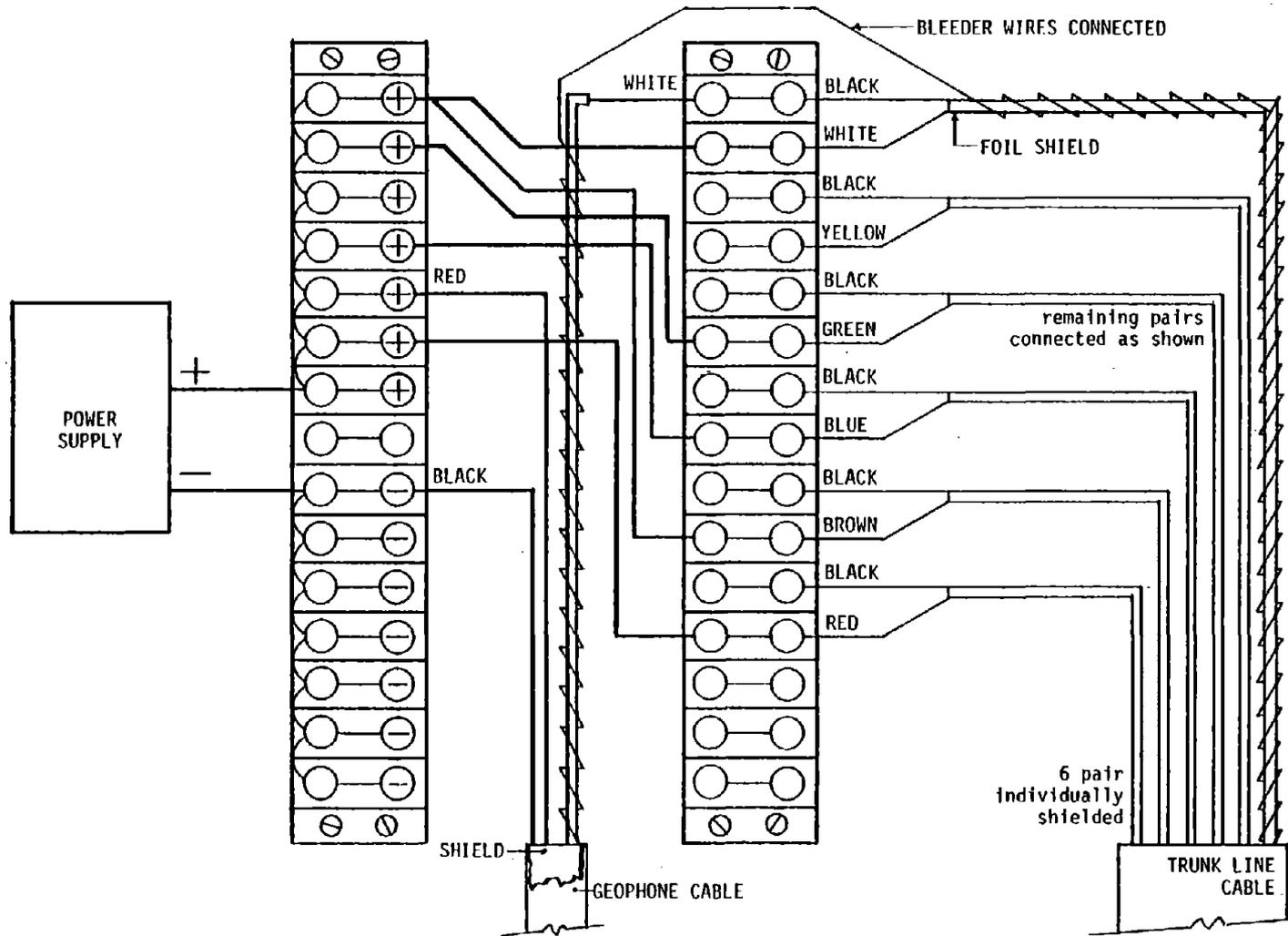
FIGURE 5-9—JUNCTION BOX WIRING DIAGRAM FOR SINGLE-ENDED AMPLIFIER SYSTEM

BLEEDER WIRES CONNECTED

FOIL
SHIELD

RED   BLACK

FOIL SHIELD

BLACK   WHITE

POWER
SUPPLY

+

−

GREEN

WHITE

BLACK

YELLOW

BLACK

GREEN

BLACK

BLUE

BLACK

BROWN

BLACK

RED

remaining pairs
connected as shown
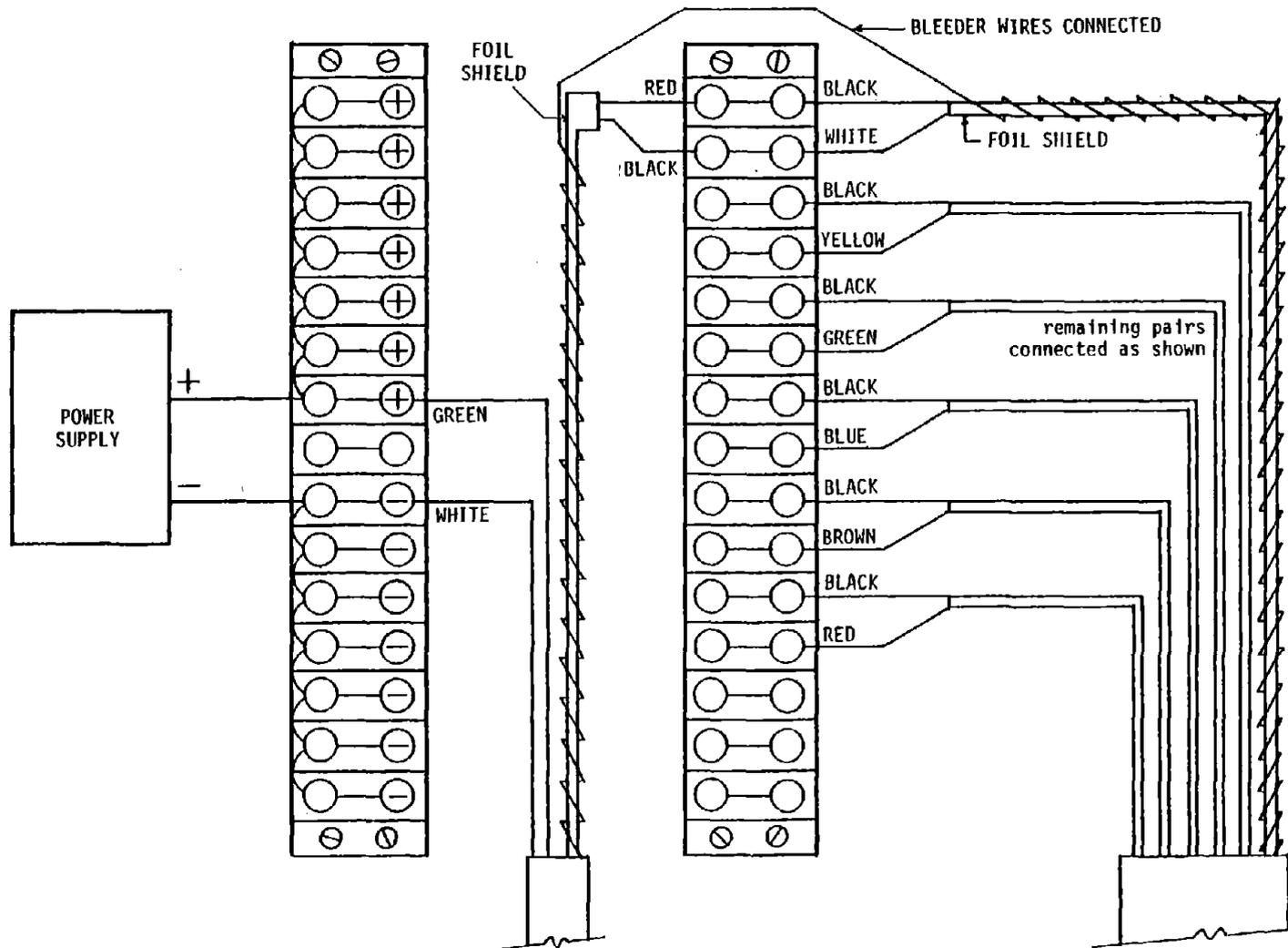
FIGURE 5-10—JUNCTION BOX WIRING DIAGRAM FOR DIFFERENTIAL AMPLIFIER SYSTEM

cable number and the color coding should be noted alongside each terminal strip, with the overall cable numbering and color coding system posted in each junction box.

For a single-ended amplifier or a differential amplifier with an unbalanced output, it is necessary to use individually shielded signal pair cables. However, for a completely differential system with a line balancing receiver at the data processor, only an overall shield is required. This is because the output cable conductors carry identical currents flowing in opposite directions, and the voltages, with respect to ground, on these conductors are of equal and opposite polarity. This results in a cancellation of the electric and magnetic fields around each conductor. Because of this flux cancellation, coupling or cross-talk between adjacent unshielded pairs will be negligible.

Not having to provide individual signal pair shielding is a real advantage with respect to cable selection. The individual shielded pair cable is not intended for severe environments, and the aluminum foil shielding is ineffective with respect to magnetically coupled electrical interference. On the other hand, high quality single or multipair cable with an overall copper shield is readily available. Besides having a better shield this cable is rated for direct burial, which makes it much better suited for the underground environment.

Electrical connection at the instrumentation station is normally made in another junction box. For an unbalanced system, the signal pairs are connected to the signal conditioning section, where all shield terminate at a single-point ground. For a balanced system, the signal pairs are connected to the line balancing receiver, and the overall cable shield is connected to the single-point ground.

Electrical connection between components of the data processing unit is normally provided by the manufacturer and usually only involves plugging in a card or electrical cord.

Voltage protection against power surges through the main power supply and through the underground cables must be provided at the instrumentation station. Any electronics connected to the underground cables should be able to withstand an over-voltage of at least 25 volts applied to signal input or output. Power to the instrumentation station should be fed through a constant-voltage transformer, and this voltage checked prior to hooking up any electronic equipment. For surface instrumentation stations, voltage protection against lightning discharges should be provided.

System Checkout

A newly installed microseismic or acoustic emission monitoring system must be checked out before being put into routine service.

Nonlocating Systems

Initial checkout procedures for single-channel portable systems or multi-geophone systems are somewhat similar. These systems should first be assembled and tested in the laboratory or office to determine that all components are working properly and to allow time for equipment operation familiarization. Of course, the instruction manuals should be studied carefully prior to operating the equipment. Upon completion of this checkout the equipment is ready for field testing.

Field testing consists of trial monitoring and hammer blow or impulse type experiments. Observing output of the monitoring equipment connected in parallel, and on an oscilloscope, is recommended. This will make the operator familiar with the visual appearance of microseismic events and cultural noise, as well as their meter/counter and audible responses.

A series of hammer blow and tapping tests will indicate the distance rock noises can be expected to propagate in different rock types. With audio-frequency systems, all sounds detected are usually recognizable, since the geophone is essentially a highly sensitive microphone. With high-frequency ultrasonic type systems, signals cannot be heard audibly unless the unit has a translator section that converts the detected high frequency noises to audible clicking sounds.

Source Location Systems

Because of the complexity of source location monitoring systems, their checkout cannot be made until all components of the system have been installed and connected and are operating. A typical system checkout would consist of the following actions:

1) Check geophones
2) Check cables, junction boxes and preamplifier power supplies
3) Check analog signals on oscilloscope
4) Set threshold levels for each input channel (0.5 - 1.0 v p-p range)
5) Set time window (50 - 100 ms range, based on travel time to geophones)
6) Load processor program
7) Key in geophone coordinates and estimated seismic velocity
8) Switch to run mode.

Once the system is running, a series of test blasts is usually made to determine an average minewide seismic velocity and to check out the functions of the timing and control and calculation sections of the data processor. This is best accomplished by setting off at least 2 sticks of dynamite close to a

geophone (some 20 ft), so the distance from source to closest geophone is small, as shown in figure 5-11. At least 2 blasts should be made at each test site so that arrival time consistency can be checked. These tests are conducted at a number of sites to determine seismic velocities throughout the monitoring area (see Chapter 6 for seismic velocity determinations). The estimated processor seismic velocity should be changed to reflect the test results as the test blasts are carried out. Next, individual test blasts should be set off randomly throughout the monitoring area to check the source location software. In general, with a good three-dimensional geophone array, one should be able to locate the blasts to within 10 - 40 ft of their origin.

If the tests produce inconsistent arrival times and poor source locations, a problem exists. The first thing one should do is recheck the geophone coordinates, then check all the wiring to ensure it is correct and channels are properly indentified. If these check out, the next step is to repeat a test blast and simultaneously record the arrival times in parallel on a calibrated multi-channel tape recorder. An analysis of the tape recorded data will show whether the problems is in the processor timing-and-control section, in the source-location algorithm, or in gain levels.

As an aid to this initial check out and testing, a good practice is to enter the test blast coordinates into a generated block program (listed in Appendix H) for a range of seismic velocities, so that estimated arrival times can be compared to actual arrival times. These comparisons may identify bad geophone locations, resulting from past mining or geologic discontinuities, as well as a poorly coupled geophone.

If no problems are found, the checkout and test period may take but a week or two. If problems exist, particularly in the wiring or the processor, testing can require months.

Maintenance and Troubleshooting

Little or no maintenance is required for a single-channel or even multi-geophone portable systems as long as care is taken in placing and handling geophones and in keeping the data processing unit clean and dry. Following any equipment failure, the first thing to do is check the batteries for low charge. If batteries are not the problem, the individual components of the system should be checked out per operating and instruction manual and with some simple tapping tests. It is not difficult to isolate the problem to the geophone, cable, data processor, or output section. Once the faulty component has been indentified, the best procedure is to explain the problem to the equipment manufacturer. If the problem cannot be eliminated with a replacement part or card, one may have to return the faulty component or unit to the manufacturer.
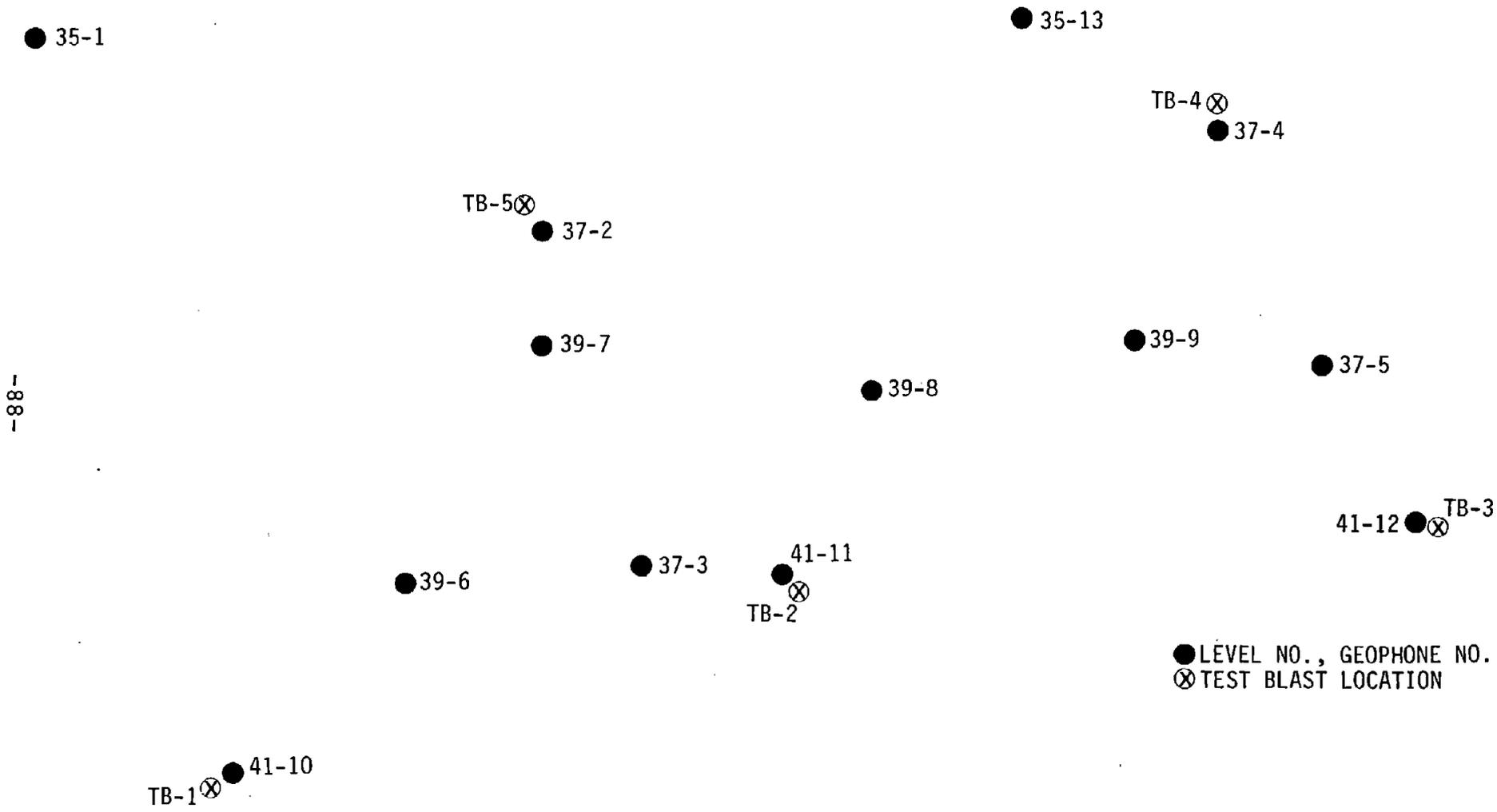
FIGURE 5-11— TEST BLAST LOCATIONS FOR SEISMIC VELOCITY SURVEYS

In source location systems or permanent multi-geophone non-locating systems, most problems are associated with the geophones and wiring or with a printing or output device. Normal problems can be determined and fixed by the operator, using good service and repair manuals usually supplied with this equipment. If this is not possible, the equipment manufacturer must be contacted and the faulty equipment serviced on site or shipped to a service center.

The geophones and cabling network must be continuously maintained at any monitoring site. Occasionally, geophones will be damaged or become detached from the rock, but maintaining the physical and electrical integrity of the cable network is a constant problem.

To locate or isolate geophone or cable problems, the operator must have electronic test equipment available. A portable battery-operated oscilloscope, a volt-ohmeter, a signal generator and a digital voltmeter is the minimum required test equipment. A portable two-way communication system is also necessary, so that voice communication over the geophone cable network can simplify troubleshooting.

The best way to insure that all channels of the system are operating correctly is to make a routine daily check of each channel. This is most easily accomplished by using a signal switching network, which allows the output signal of any channel to be heard and displayed simultaneously on an oscilloscope. All channels can be checked and irregularities noted in a few minutes. For a properly operating system, all geophone signal outputs will essentially look and sound alike, and their output voltage levels will all be within the normal operating range -- usually some 5 - 50 millivolts.

For a typical underground installation using balanced output preamplifiers (60 db gain and 1 v/in/sec transducer sensitivity), unbalanced receiver amplifiers at the data processor, and a single-point cable shield ground, the operating noise level of each channel is in the 5 millivolt range. An excellent installation, using identical geophones but with a completely balanced system and dry cables, had an operating noise level of only 1 millivolt. A poor installation, with a system identical to the previous example, had an operating noise level in the 1-volt range, with crosstalk between some channels.

When any geophone signal output is found to be abnormal, that geophone and its wiring should be immediately checked out. Typical examples of problems are given in table 5-1.

Table 5 - 1 Electrical Problems, Causes and Corrections

Problem	Cause	Correction
No audible noise or observable geophone signal	Shorted cable or dead geophone	Check cable and geophone
Bouncing signal on oscilloscope and intermittent static audio noise	Bad geophone or wet cable connection	Check cable connection and geophone
Low level 60 Hz signal on oscilloscope with low hum on audio	Minor shielding or grounding problem	Check shield connections and wiring
High level 60 Hz signal on oscilloscope with high level hum on audio	Major shielding or grounding problem or cut cable	Check cable, shield connections and wiring
Weak or no response on both oscilloscope and audio for several geophones	Bad power supply or cut trunk line	Check junction box power supply and trunk line
High frequency signals on oscilloscope and hiss or whine sound on audio	Mechanical noises from air line leaks fan motors, etc.	Check mechanical equipment near geophone. Fix problem or shield or move geophone

When trouble-shooting, one first should determine whether the problem is in more than one channel, then isolate the bad channel or channels. One normally first disconnects the geophone and establishes voice communication back through the cable to someone in the instrumentation station. If voice communication can't be established or is not clear, the problem is obviously in the cable. If the cable appears all right, the voltage to the geophone is then checked with the voltmeter. If the power check proves positive, the problem is apparently in the geophone. The geophone should be reconnected to determine if the connector may have been the cause. If the geophone is still bad, it is replaced.

Cables can be checked by measuring cable resistance from point to point with an ohmmeter to check continuity. Conductor resistances per 1000 ft for copper are:

18 gage	6.6 ohms
20 gage	10.5 ohms
22 gage	16.8 ohms.

The location of a cut or short can also be calculated, taking into account the double back length, from the ohmmeter readings. The suspected location, rather than the entire cable length, can then be inspected. The bad section of cable is spliced or repaired. In some instances the cable damage may not be obvious. In these cases the cable is usually cut, good sections determined, and new sections spliced to the good sections. When working with multi-conductor cable one must be very careful in re-splicing and waterproofing the splice.

A useful item of equipment for checking cables and geophone preamplifiers is a portable audio signal generator having a sine wave and fixed voltage output. The signal can be fed into the preamplifier through the geophone connector or can be put directly on the cable. The problem can then be isolated to the geophone, preamplifier or cable.

Use of junction boxes makes cable checking easier for both single or multipair cable systems. Cable problems can then be more easily isolated between junction boxes. An ohmmeter or a cable-fault detector can then be used to locate the break or bad section. Water seeping from cable ends at a junction box is diagnostic of a cut in the cable jacket. This usually produces a noisy section of cable and attenuation of signals. Cables, particularly single pair cables in multiple runs, should be marked at frequent intervals for ease of identification.

Finally, it cannot be overemphasized that the key to minimizing cable maintenance is installing high quality cable and wiring it correctly.

Equipment malfunctions in the data processing unit are rare. However, if malfunctions do occur and service manuals are available, the operator or electrical maintenance crews should follow the manuals to the limit of their capabilities. Assistance from the manufacturer likely will be required, and an on-site service call is preferable to shipping the unit out for repairs.

As complex electronic equipment is not readily maintained by mine personnel, service maintenance contracts should be obtained for the data processing unit and any peripheral computing,

plotting, and display equipment. Arrangements for on site service on other components of the system should also be established.

References

1. Rowell, G. A. and L. P. Yoder. The Effect of Geophone Emplacement on the Observed Frequency Content of Microseismic Signals. Proc. Third Conf. AE/MS Activity in Geologic Structures and Materials, Penn. State Univ., October 1981, Trans Tech Publications, in Press.

2. Lepper, M.C., Poland, A. P., and C. T. Mullis. A Microseismic System for Monitoring Slope Stability. Bu Mines RI8641, 1982, 64 pp.

CHAPTER 6

OPERATING A MICROSEISMIC SYSTEM

Microseismic or acoustic-emission activity indicates a structure may be having difficulty adjusting to the applied loads. To use this phenomena in understanding the structure's behavior and assess its stability, one must first detect and record the microseismic data.

Gathering Data

For geotechnical applications, traditional single-channel microseismic monitoring involves detecting audio frequency events generated in rock or soil structures.

Single-Channel Monitoring

The basic procedure is to visit known or suspected problem areas and gather the microseismic data. This is achieved by placing the geophone in good contact with intact rock or soil and operating the equipment for a 15 to 30-minute period. Detected events are counted or recorded, and the general ground conditions at the site are observed and noted. Extraneous noise, though not counted, is noted if recorded. This procedure is repeated for a number of locations in and around the unstable zone. Other unstable or suspected unstable zones are monitored in like manner. This monitoring, shown pictorially in figure 6-1, is repeated at frequent intervals, the frequency depending on the level of the microseismic activity and the potential hazard. For example, active mining in popping and cracking bad ground should be checked on at least a daily basis. A slowly failing pillar or a slow moving slope may require only a weekly check. The field data and notes should be maintained in permanent log books. This permits future data analyses and provides a past history of all monitoring.

Using this type of monitoring, one can cover any mine area or monitoring site on short notice and also note extraneous noise and ground conditions. However, this method has a number of serious disadvantages. Monitoring periods are very short, and the visits must be made during quiet times. This limits the number of sites that can be monitored on a daily basis. The quality and reliability of data are largely a function of the operator's experience and enthusiasm. And, one cannot determine the exact location of the microseismic event, only that it is in the general vicinity.

High-frequency portable equipment has been developed which responds in the 35 - 100+ KHz range, to overcome the disadvantage of monitoring only during quiet times. This development
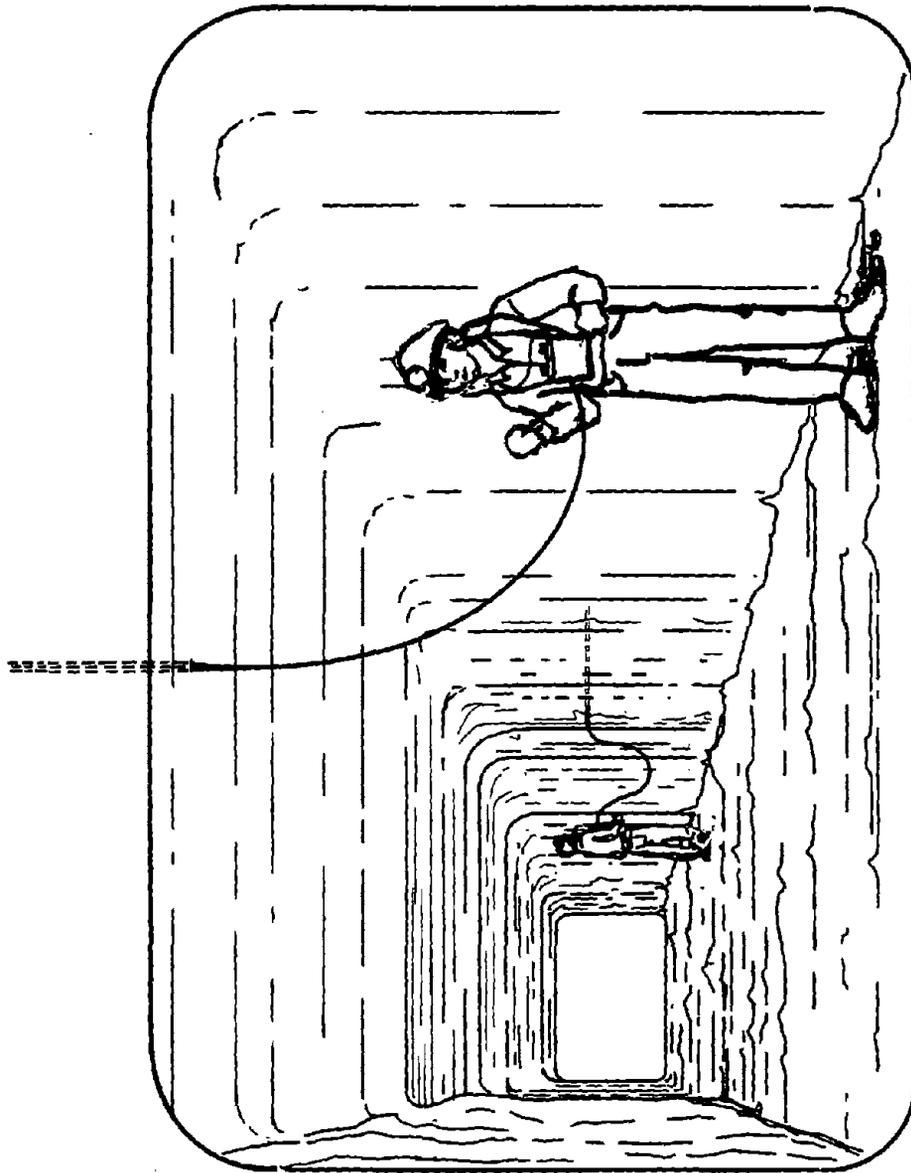
FIGURE 6-1— PORTABLE MICROSEISMIC MONITORING

shows much promise for applications where continual noise is present, such as continuous mining of coal. The extraneous machine noise is below the frequency range of the monitoring equipment, hence does not mask the microseismic signals. The Bureau of Mines has reported very encouraging initial field results, and a commercial monitoring unit has now been developed (1). (USBM Contract No. H0272009 Final Report, "Microseismic Roof Fall Warning System Development, Field Trials and Commerical Prototype Fabrication", May 1980)

Because high frequency microseismic signals do not propagate long distance, the geophone must be relatively close to the unstable zone to be effective. Present practice is to mount the geophone against the back and set the data processing unit in a safe place. Monitoring, which is continuous, records the number of events detected and the time an event is above threshold (an energy estimate). Plans are to adapt both geophone and the processing unit for mounting on continuous mining machinery. The data processor will trigger an alarm to warn the machine operator of an imminent roof fall.

Multi-Geophone Monitoring

To overcome the deficiencies of single-channel monitoring, an array of geophones can be monitored simultaneously and used to cover a number of suspected unstable zones. Monitoring can be continuous or programmed to coincide with quiet or inactive mining times. Because the equipment is comprised of single-channel components, the same type data is gathered with some 8 or more channels as with a single-channel system.

Amplitude comparison of multi-geophone data better indicates the source of detected events. When more than one geophone detects the same event, the channel showing the largest amplitude should be closest to the source. The incoming data is counted or recorded, providing a permanent, unbiased monitoring record. However, the advantage of an operator's daily observations of extraneous on-site noise, ground conditions and excavation activities are lost.

Source Location Monitoring

Data gathering with a computer-controlled source location or rock-burst-monitoring system continues automatically around the clock. Microseismic and seismic events, as well as blasting events, are detected and their sources located. Normally all data from each event is printed out sequentially as it occurs, as shown in figure 6-2. For arrays covering specific areas, the source locations can be plotted on plan and section maps as each event is detected. The data processing unit may also be recording the total number of events detected, total energy,

```
                        ┌─────────X or east coordiante

                           ┌───────Y or north coordinate

                              ┌──────Elevation (see level datum)

                                 ┌──Year

                                     ┌─Day (Julian)

                                         ┌─Hour ┌Minute ┌Second

        001034000828-01810001978000215000008000027000043
```
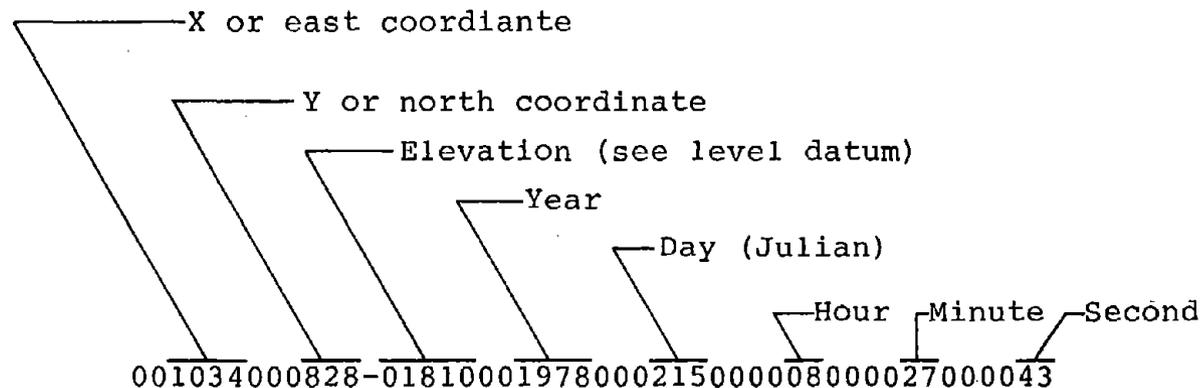
GEO   TIME   ENERGY   000032 – Relative energy as determined
                                     by intergrator

```
              ┌21000000 ─── First phone hit
              │15000009│
              │14000144│
              │22000152│
              │13000221│
Geophone ─────│08000229├───── Arrival times to subsequent phones in machine language
Designation   │10000244│
              │16000271│         i.e., 9 'clicks' = 9 x .00005 sec. = .00045 sec.
              │23000299│
              │12000340│             450 micro seconds @ velocity of 18,000 ft/sec wave
              │06000396│
              └17000526┘                travels = 8.1 feet
```

FIGURE 6-2— DATA PRINTOUT FROM SOURCE LOCATION MONITORING SYSTEM (3)

current microseismic or energy release rates, etc. This data can be printed out on a programmed time schedule or requested at any time through the keyboard terminal.

It is apparent that a large number of events (hundreds) can occur daily if a mine or other structure is even moderately active microseismically. Analysis of such large amounts of resultant output data is very time consuming and may well be completed too late for remedial action. Thus, for real time data analysis and plotting, it is becoming usual practice to transfer large volumes of daily output data to disk file storage on an adjacent or remote, interactive minicomputer.

A number of problems encountered during continuous monitoring near underground mining activity may cause loss of data. The audible level of underground drilling noise is high enough to exceed the threshold voltage on one or more channels. This causes almost continuous activation of the timing and control section of the data processor. Large mine blasts or large seismic events will normally overdrive the amplifiers of some geophones, producing false or echo events for up to 15 seconds following the event. And spurious electrical noise can cause any number of false events, depending on the electrical problem. Continuous triggering of a monitoring system is usually apparent from small lights flashing on channel input cards each time a threshold is exceeded, or from status lights flashing on the computer part of the processor.

The drilling noise problem is dealt with in a number of ways, from manual to fully automatic countermeasures. The operator can check each geophone, using a monitoring switch, to isolate the triggering channels. These channels are then manually switched off until the drilling stops, or their threshold levels can be raised above the drilling noise. This solution is not generally satisfactory, since it requires almost continuous checking by the operator. New microprocessor-based timing and control sections have the capability to recognize drilling noise, latch the affected input channels closed, and return them to service when the drilling stops. The Bureau of Mines has handled this problem at one of their underground monitoring locations by developing a hardware-software drill supress routine. This basically consists of checking 3 channels at the end of each time window. The two drill detection channels are near the stope or stopes being monitored, while the third channel is at some distance from these stopes. If the signal levels on both drill detection channels are still above threshold and the signal level on the third channel is below threshold, the triggering event is rejected as drilling noise. If the signal levels on all three channels are still above threshold, the triggering event is accepted as a microseismic event. This solution works well for small-area monitoring and, with only minor software changes, could be adapted for

large-array mine-wide monitoring. However, it does not stop continuous triggering of the timing and control unit. Another solution, developed for acoustic emission monitoring, is the floating threshold. The threshold level adjusts itself automatically to the average background noise level. Drilling or other continuous mine noise then become the background noise level, and the thresholds of affected channels are automatically adjusted.

Coping with equipment overdrive caused by large blasts or large seismic events is somewhat difficult. The Bureau of Mines, again for small-area monitoring, and to record all bursts, has used a split input with reduced amplification to handle the problem. A 24-channel system is used to look at 12 channels with high-gain amplification for low-level events and the same 12-input channels with low amplification for high-level events. Logarithmic or automatic gain-controlled amplifiers could be used, but the problem has not yet been significant enough to warrant the added equipment expense and complexity.

Spurious electrical noise usually produces electrical spikes that may trigger all channels simultaneously. Obviously, the best way to deal with this problem is by using good wiring and grounding practice. This normally eliminates spurious electrical noise. The problem has been dealt with, however, in software-controlled timing and control sections by considering an event an electrical spike if more than 3 geophones are triggered during a minimum time interval. If 4 or more geophones have identical arrival times, the event is rejected as electrical noise.

While a great deal of time and money is expended gathering microseismic data, not enough time and effort is spent in gathering data to determine the cause of the problem. The microseismic data is but the response of overstressed rock to loading. To be meaningful, analysis and interpretation of this data must include the site geology, rock properties, loading conditions, excavation geometery and sequence, and any other field measurements that have been taken. Hence, visits to problem areas must be made on a continuing basis. In addition, observations by both workers and supervisors should be solicited as they are closer to the problem and usually develop a good feel for how the rock or structure is behaving.

Analysis of Data

Raw microseismic data, gathered by manual or automatic monitoring, must be presented in a form such that anomalous or diagnostic trends are recognizable. The usual procedure is to carry out and present the results of data analysis with respect to a particular structure or parts of a structure.

Knowledge of the source of the microseismic events pinpoints the problem area. With single-channel monitoring the geophone is located in the structure, hence the microseismic events detected are presumed to be located within the structure. With multi-geophone monitoring each geophone may be located in one or more structures and that data is analyzed according to the location of each geophone. With source location monitoring the computer locates the origin of each detected event to a point in space, which is then related to a specific structure or parts of a structure. Hence, data analysis procedures for any type of microseismic monitoring are basically the same, rock noise occurrence data is compiled for specific areas. The data for any structure is tabulated for statistical analyses, displayed for pattern or anomalous trend recognition, and plotted to delineate potential problem areas. Thus, data analysis is based both on the location of rock noise occurrences and the characteristics of the rate at which those noises occur. Where necessary, the raw data is corrected prior to the data analysis.

Microseismic Counts

Microseismic data is usually analyzed to make stability judgements by examining the number of events occurring in any particular structure or parts of a structure. This is done by summing the number of events over a given time interval to determine the microseismic rate. The microseismic rate is then plotted against time, usually days or hours. An example of this type of plot is shown in figure 6-3. Similarly, if threshold crossings for each event were counted, the threshold-crossing rate would be plotted versus time. It should be noted that the numbers involved in threshold-crossing plots are much higher than those in event-count plots, since large events may produce large numbers of threshold crossings because of their longer duration.

Microseismic-rate plots are usually made even when monitoring is not conducted continuously. With continuous monitoring, plotting total daily events, as shown on figure 6-4, or threshold crossings is the more common practice.

The classic, and looked for, anomalous microseismic pattern is a sudden high rate or count, followed by an equally sharp decrease in microseismic activity. This is sufficient reason to examine the area producing the anomaly and to look for the cause of a potential problem.

Energy Release

Microseismic rate or count plots treat each event equally, regardless of the magnitude of the event. Since both more and bigger events usually precede a failure, plots of the amount
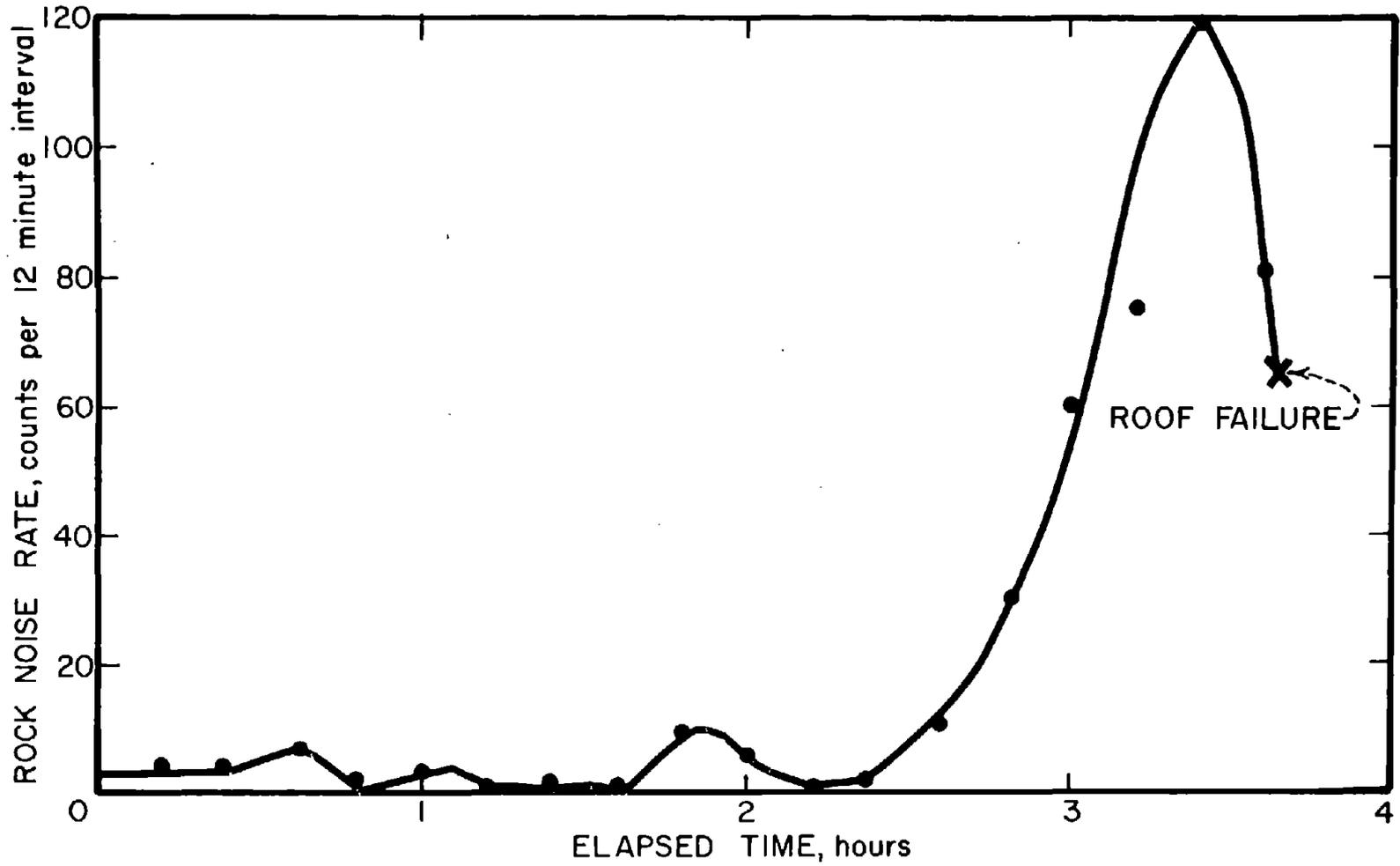
FIGURE 6-3— MICROSEISMIC RATE VERSUS TIME PLOT (2)
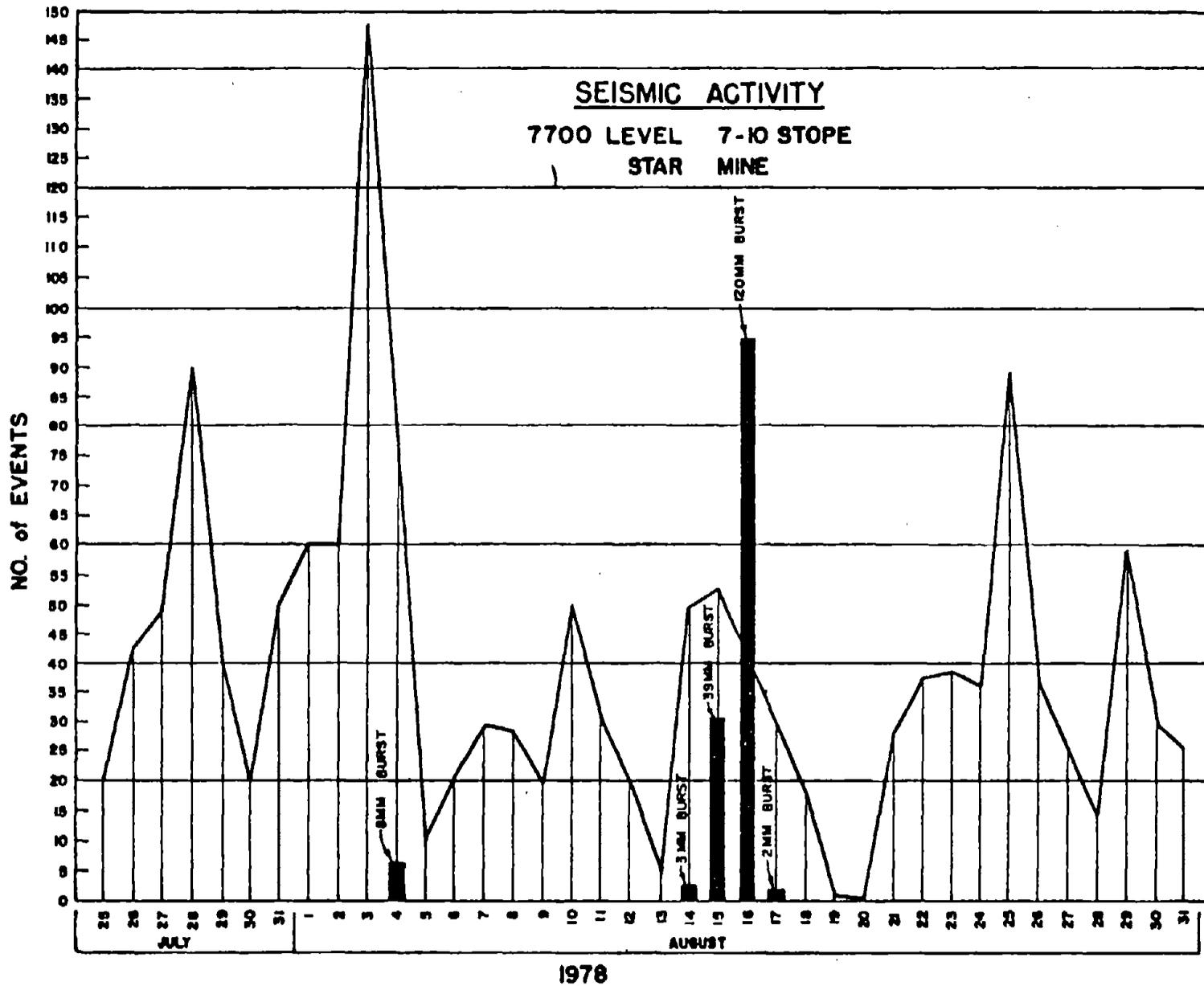
FIGURE 6-4— TOTAL DAILY EVENTS VERSUS TIME (3)

of released energy are often more diagnostic than are plots of microseismic rate. The data presented in figure 6-5 shows that the sum of seismic energy released daily indicated an anomalous buildup prior to the occurrence of a rock burst, whereas the number of events occurring daily did not. It should be mentioned that threshold crossing counts somewhat represent the events magnitude since larger events result in more threshold crossing.

Because there is no standard method for computing microseismic energy, all energy numbers or rates are relative and apply only to a particular study. Energy numbers are computed by squaring the amplitude of the event, integrating the wave form over a time interval (by any of several methods), determining the time above threshold, determining the event duration, and by combinations. Regardless of the calculation method, the data is usually plotted as an energy per time-interval over a chosen time span or as total energy per day. Again, any anomalous increase or decrease in the data is looked for which would indicate a potential problem in a particular structure.

Energy data would perhaps be more useful if energy at the source were calculated rather than energy detected at the geophone. For source location systems, this calculation is possible if an energy propagation law is determined for the surrounding rock mass, since the distance from source to geophone is known. Procedures for calculating the energy of an event and the energy at the source are given in Appendix F.

Since events tend to be of larger magnitude as failure is approached, it follows that the waveform frequencies of events should decrease as failure is approached. Considerable research has been carried out to determine if this frequency down shift is readily recognizable, but to date a diagnostic drop in waveform frequencies of detected events prior to failure has not been verified.

Energy Per Event

If both the microseismic counts and the energy released are recorded, a ratio plot of the energy per event can be determined. In some high-frequency monitoring, particularly with regard to roof falls in coal mines, this ratio has a sharp and diagnostic peak immediately prior to a failure, as shown in the example on figure 6-6.

Blast Equilibrium

Daily mine or construction blasting changes the excavation geometry, and the resulting stress adjustment in the surrounding structure generates microseismic data. The time required, because of the reshaped opening, for the structure to regain equilibrium, (settle down microseismically) is a measure of the structures stability. Stable structures normally regain

```
                  DAILY SUM OF SEISMIC ACTIVITY FOR 1300-1300 HOURS INTERVAL
                         SEISMIC EVENTS                              SEISMIC ENERGY

        JDAY     10    20    30    40    50    60        250   500   750  1000  1250  1500  1750
               I----I----I----I----I----I----I----    I----I----I----I----I----I----I----I
         88  I*                                        I                                      I
    B    89  I*********                                I*********                             I
         90  I**                                       I                                      I
         91  I                                         I                                      I
         92  I**                                       I                                      I
         93  I                                         I                                      I
    B    94  I*********                                I******************************        I
         95  I**                                       I                                      I
    B    96  I*******                                  I***                                   I
         97  I*********************                    I********                              I
         98  I***                                      I                                      I
         99  I**                                       I                                      I
        100  I                                         I                                      I
        101  I*                                        I                                      I
    B   102  I*****                                    I*****                                 I
    B   103  I***                                      I*******                               I
        104  I                                         I                                      I
        105  I                                         I                                      I
        106  I                                         I                                      I
        107  I                                         I                                      I
        108  I                                         I                                      I
        109  I*                                        I                                      I
        110  I*                                        I                                      I
        111  I*                                        I                                      I
        112  I                                         I                                      I
        113  I**                                       I                                      I
        114  I*                                        I                                      I
    B   115  I**                                       I*                                     I
        116  I**                                       I                                      I
    B   117  I**                                       I***                                   I
    B   118  I***                                      I************                          I
    B   119  I*****                                    I*                                     I
        120  I**                                       I**************                        I
        121  I                                         I                                      I
    B   122  I                                         I                                      I
    B   123  I**                                       I**                                    I
        124  I*                                        I*                                     I
    B   125  I*                                        I                                      I
    B   126  I*                                        I******                                I
        127  I                                         I                                      I
        128  I*                                        I                                      I
        129  I*                                        I*                                     I
    B   130  I**                                       I********                              I
    B   131  I****                                     I*********************************     I
    B   132  I******                                   I****************                      I
        133  I***                                      I                                      I
        134  I                                         I                                      I
        135  I                                         I                                      I
        136  I*                                        I                                      I
    B   137  I*****                                    I****************                      I
    B   138  I**********         ROCK  BURST           I************************************* I
        139  I*                                        I                                      I
               I----I----I----I----I----I----I----    I----I----I----I----I----I----I----I
        JDAY     10    20    30    40    50    60        250   500   750  1000  1250  1500  1750
```

FIGURE 6-5— MICROSEISMIC DATA PRECEDING A ROCK BURST (4)
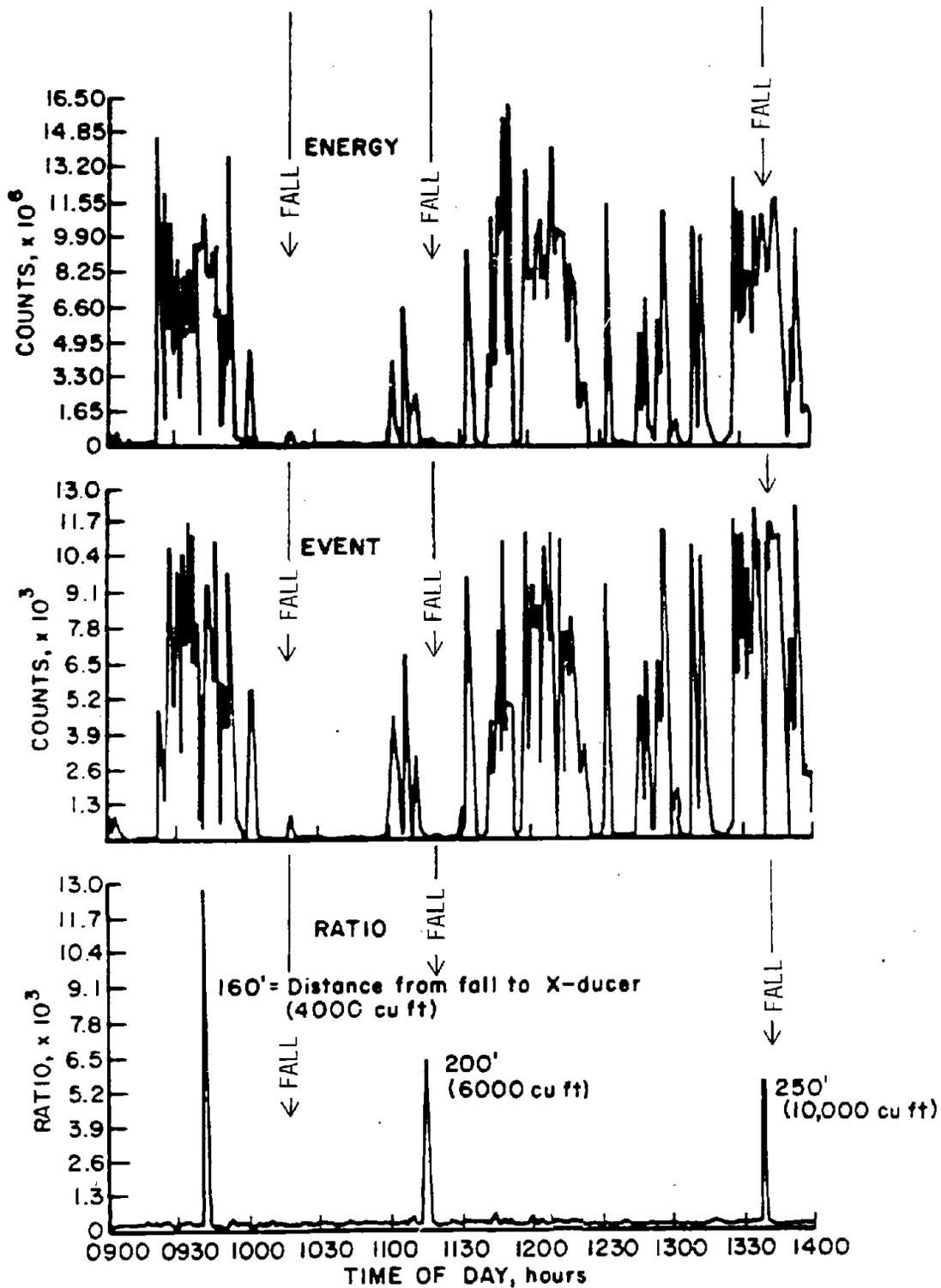
FIGURE 6-6— ENERGY PER EVENT RATIO PLOT SHOWING DIAGNOSTIC
PRECURSORS PRECEDING FAILURES (1)

equilibrium (quiet down) within 30 minutes following blasting; whereas unstable structures will continue to work or adjust for hours, emitting microseismic noise. Usually the amount of energy released is more diagnostic than are microseismic counts, as it is common to observe fewer but larger events as an unstable structure adjusts. Figure 6-7 shows example plots of stable and unstable structure response following mine blasting. The stable structure rapidly settles down after blasting, whereas the unstable structure continues to emit large amounts of energy.

Microseismic Source Location

The goal of any microseismic monitoring is the location of potentially unstable areas in rock, soil or man-made structures. With single-channel monitoring, an estimate of the source of detected events can be made by probing with the geophone in the suspected unstable area. Presumably when the microseismic noise is the most frequent and intense the geophone is closest to the source. With multi-channel monitoring, an amplitude comparison for the same event will provide an estimate of the source. The closest geophone should detect the event first and register the greatest amplitude. These estimates are usually very qualitative--within a few hundred feet of the actual source. An accurate, mathematically determined, source location requires that the event be detected by at least 4 geophones and the first-arrival times of the microseismic wave at these geophones be precisely known. Also required are measured geophone coordinates, and an accurate seismic velocity model for the area monitored. This information is then used in a set of equations to calculate the x, y, z source coordinates. The development of these equations and their solution is a complicated mathematical exercise (5 - 10). An overview of source location techniques is presented in Appendix G.

Both on-line and off-line computer calculations of microseismic source locations produce only best estimates of the true source location. Variations in seismic velocity, unclear identification of first arrival times, an unknown source time, less than ideal geophone arrays and possible interference from blasting or another simultaneous event, introduce errors. These estimates are typically accurate to within 10 - 40 ft. The majority of events are located accurately enough to delineate potential problem areas to a particular structure or part of a structure. This is the goal of any field monitoring, which has been shown to be adequate in practice. Concern over more exact location of the source is not warranted.

Plots of located events show where stress is building or movement is occurring. Typical stress buildup is plotted in figure 6-8. The contours of rock noise density delineate stress
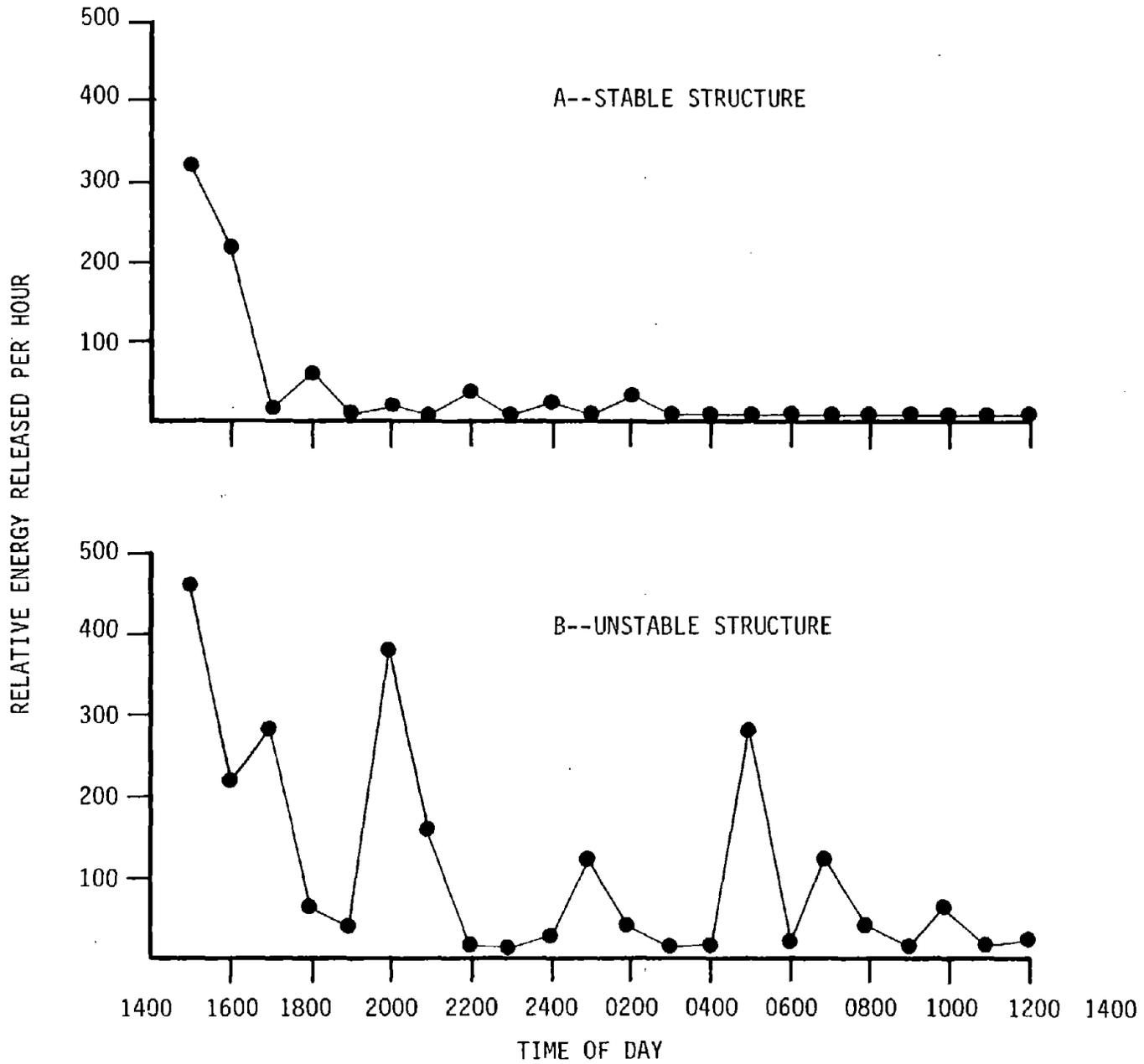
FIGURE 6-7— STRUCTURE RESPONSE FOLLOWING MINE BLASTING
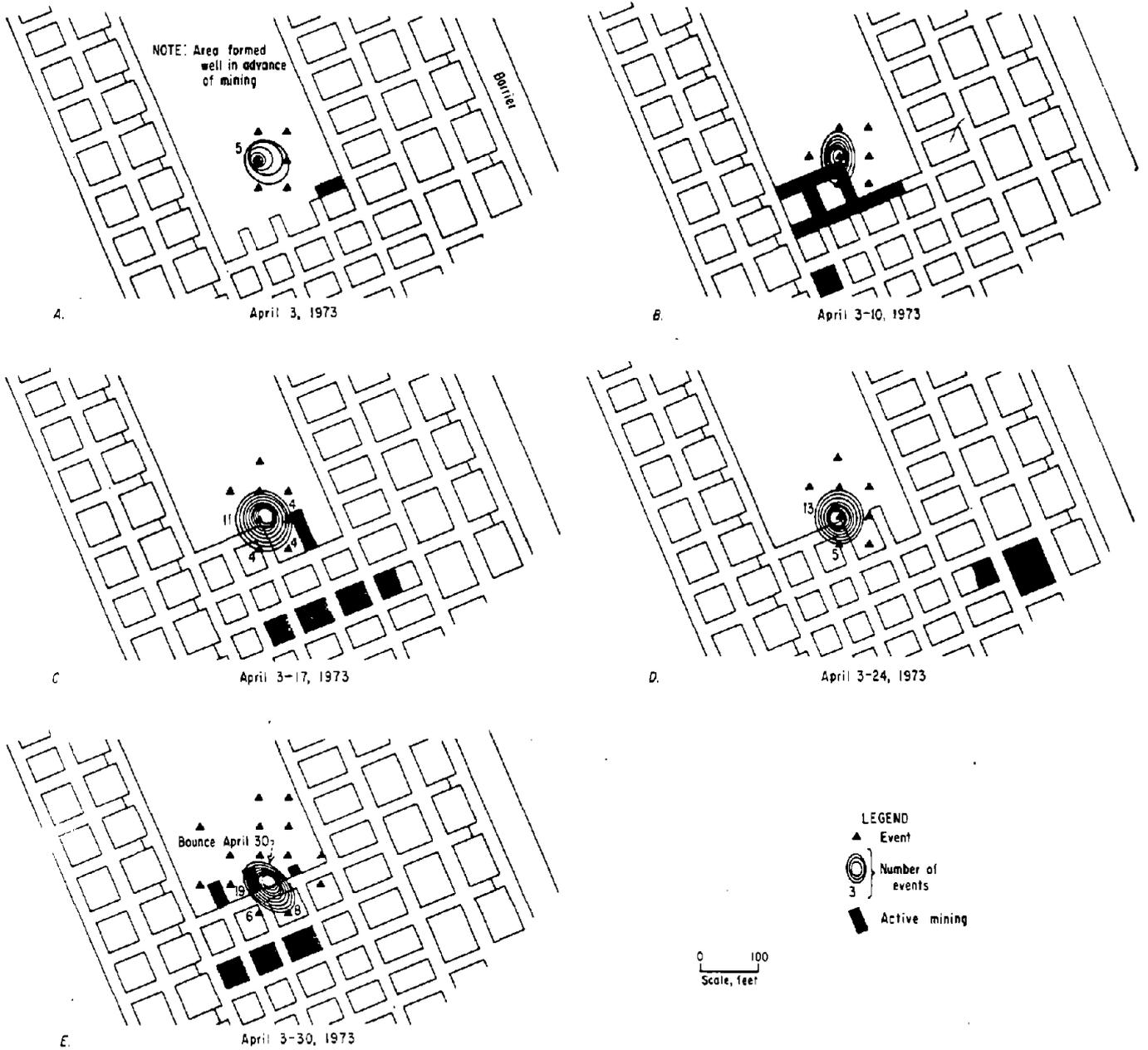
FIGURE 6-8— CUMULATIVE NOISE LOCATIONS SHOWING GROWTH OF STRESS BUILDUP
PRIOR TO COAL BOUNCE (2)

concentrations. On-line plots are in real time or plotting can be done at the operator's convenience using data filed in disk storage. In the latter case, plots can be constructed for a particular area over any time period. The selection of time period is based on the type and severity of the problem.

Seismic Velocity

Seismic-velocity values must be determined for any monitoring location before microseismic events can be accurately located. Seismic velocity values also supplement the microseismic data with respect to locating, mapping and evaluating areas of increasing or decreasing stress. Stress buildup in a structure is normally accompanied by increased seismic velocities to geophones surrounding the structure as well as by increased microseismic activity.

For minewide monitoring, where assigning a microseismic event only to a particular mine structure is sufficient, an overall, average seismic velocity is used. When detailed stope or structure monitoring requires greater source-location accuracy (within 10 feet), a separate, calibrated seismic velocity may be needed for each geophone. However, seismic velocity varies because of different travel paths, geology, rock conditions, mined openings, etc., and the microseismic events are generated randomly throughout the structure; thus choosing the correct velocity for each geophone becomes a complex problem. Experience has shown that use of average seismic velocities is sufficient.

Seismic velocities through structures can be determined using standard seismic velocity survey equipment, such as a signal enhancement seismograph, or if a source-location system is in operation, by setting off test blasts at known points. Seismic surveys repeated over a period of time will reveal increases or decreases in seismic velocities through structures. These data can then be used to supplement microseismic and field data.

Data Processing

Whether data is gathered manually or automatically, it must be checked and analyzed in a consistent and routine manner. For the nonlocating type monitoring systems, this may only involve scanning the counted or recorded data to insure events detected were real and summary statistics and plots are correct and up to date. For source location monitoring, the checking and sorting of the data usually requires a major effort.

The usual output from source-location monitoring in geotechnical applications is sequential printing of data for each

detected event. The operator must then examine the print-out to:

1) Check events for consistency of arrival times and source location.

2) Reject blasting events and sort out good events occurring with the blasting.

3) Sort events with respect to particular structures.

4) Tabulate event statistics and plot data for each structure.

5) Tabulate overall event statistics and make overall plots of data.

Once familiar with a system and the data analysis procedures, an operator can scan the data print-out and relatively quickly and easily check and sort out the data.

Mislocated events are obvious to an experienced operator because the source location does not correspond to the arrival time sequence. That is, the located event should hit the closest geophone first, and successive geophones corresponding to their respective distances from the source. Mislocated events are usually because of interference from one or more geophones triggered by the simultaneous occurrence of another event or local cultural noise. The operator corrects mislocated events by a procedure shown in Appendix H.

Mine blasts normally occur during specific time intervals 2 or 3 times per day. These events have a characteristic range of energy levels and their locations can be assigned to particular stopes or headings; hence, they are easily recognized as blasting events. For example, the blasting in a particular stope may result in relative energy units ranging from 60 to 100. Microseismic events will be located some distance from the blast events and will have lower energy levels, in the 0 to 60 range. A seismic event will likewise be located some distance from the blasting events, but will have a higher energy level, above 100. With experience, the sorting of real data from blasting data is not a problem, unless an event is completely masked by a blast or blast echo.

After blasting is deleted, events are checked and corrected, then sorted with respect to a particular structure. The data for each structure is tabulated and plotted, and overall tabulations and plots complied. Events that can't be unscrambled are put into a no-plot category. It is apparent that, when hundreds of events are detected and located daily, some form of automatic, on-line data processing is necessary. Output of the data-processing unit must be transmitted to a separate data-processing computer, or at least stored on some mass-storage device.

Mining companies with rock burst monitoring systems are now upgrading their systems to include automatic data analysis and processing. Real-time updated plots for any monitored structure will make analyses much more timely and efficient.

Interpretation of Microseismic Data

The microseismic data, when tabulated and plotted, shows how particular structures are responding to changing geometric and/or loading conditions. Increasing microseismic and energy release rates for a particualr structure indicate increasing stress or movement. Source location plots show where zones of increasing stress or movement are developing within the structure. A seismic velocity survey may show whether the structure is loading and storing up energy prior to failing, or whether the structure is unloading by slowly and gradually failing.

The microseismic data, by itself, is only one piece of information with respect to the stability of any structure. It must be combined with the mining, geological and rock mechanics information, as well as past microseismic history. When all this information is combined, the reasons for anomalous microseismic data usually becomes clear, and corrective or remedial measures can be taken to prevent occurrence of a potential problem. In some instances warning of an imminent failure may be accomplished.

The utilization of past microseismic history must be approached with caution. A diagnostic sequence of microseismic events that preceded a failure in one structure may not precede failure in another structure, or even a second failure in the original structure. Different geologic conditions and different loading conditions make the microseismic response of each structure somewhat different. Though general microseismic patterns may be diagnostic with respect to a failure, individual patterns for specific structures may be almost unique. Therefore, a great deal of caution must be used in applying criteria established for one structure to another.

The microseismic data will usually indicate the problem's location and whether the problem is becoming more serious or is stabilizing. It will also provide a means of evaluating any remedial measures taken to prevent a rock failure. Only on rare occasions has data interpretation been successful in predicting the time of failure occurrence.

However, once a person has gained experience at a particular mine or site he should be able to develop some potential-failure criteria based on microseismic data. The more uniform the geology and ground conditions, mining geometry and sequence, loading conditions, etc., the greater the chance of establishing

characteristic microseismic responses to mining or excavation.
In some coal mines with uniform conditions, success has been
achieved in using microseismic monitoring equipment, with
built-in diagnostic pattern recognition, to sound an alarm
when a preset microseismic rate, energy rate or combination
of the two is exceeded.

While microseismic equipment continues to become more
sophisticated, there has been little real improvement in the
utilization of the microseismic data during the past 10 years.
This may be due to a preoccupation with looking for character-
istic patterns rather than relating the available microseismic
data to the on site conditions and problem causes. It is still
not possible to have cook book type procedures for microseismic
monitoring. There are no standard data analysis procedures
that can be uniformly applied for predicting a failure.

It must be emphasized that the microseismic technique is
only a tool that provides information about rock structure
behavior to applied loads. This tool by itself does not pre-
vent or solve problems. The data from this tool, when correctly
interpreted, can lead to the recognition and causes of a prob-
lem. Utilization of this data obviously requires both experi-
ence and knowledge in the particular problem area.

Training

Operating a microseismic monitoring system is usually not
difficult, but finding trained personnel is. Normally at
least two persons are required to staff a monitoring project--
a technician to maintain the system, do the monitoring, and
make preliminary data analyses; and an engineer to interpret
the microseismic and geotechnical data, make stability
evaluations, and outline corrective action. These are both
full time positions.

Ideally the technician has a couple of years of engineering
education, a good background in electronics, and a knowledge of
computers. The engineer in charge should have a strong back-
ground in rock mechanics and a good background in mining, geo-
logy and computers. Electronics is desirable but not neces-
sary. Both must be inquisitive, enthusiastic, and able to
communicate with workers and management.

Basically, no formal training in microseismics is available.
The short courses in acoustic emission given by equipment manu-
facturers are not very geotechnically oriented. Only occasion-
ally do rock mechanics short courses devote one or more lectures
to microseismic monitoring. In short, most training is gained
on the job and by reading the published literature, touring
government or university research facilities conducting micro-
seismic studies, and by visiting field monitoring sites of

mining companies or research organizations. Where a monitoring system is already in operation, on the job training is greatly aided by maintaining well documented files on equipment, monitoring and data analysis procedures, and all logs, notes and reports written.

With available training, including short courses in both rock mechanics and computer programming, new personnel normally require one year's experience to become familiar with the equipment, the microseismic method, the rock mechanics problems, and gain the confidence of working and supervisory staff. The monitoring personnel can then utilize the microseismic data to improve ground control and safety in the everyday mining or construction operation.

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CHAPTER 7

USING MICROSEISMIC DATA

Use of microseismic data is illustrated by the following case histories.

General Underground Monitoring

The single-channel surveys carried out by Industrial Minera Mexico in their underground mines are examples of using microseismic monitoring to improve ground control. Potentially hazardous working areas are reported to the rock mechanics engineer, who then includes them in his routine monitoring program. The effectiveness of this program was demonstrated during the drilling and blasting of sublevel long holes at the San Diego mine of their Santa Barbara Unit (1).

To increase production, a wide section of their vein (39-66 ft in thickness) was developed and mined by sublevel open stoping, rather than by the usual shrinkage or cut-and-fill methods. In 1975, three sublevels were driven between the 800 and 930 levels, some 1800 ft below the surface. These sublevels were driven full-vein-width without reinforcement. Mining also began in 1975, and the blasting of the rows of holes continued for some two years with no real problems. However, as mining continued and the amount of open ground grew larger, the unreinforced roof conditions began to deteriorate, particularly in the areas immediately adjacent to the open stope. By the end of 1977 small roof falls were beginning to occur along the sublevels. A program of microseismic monitoring was initiated in 1978.

Two operators checked the troublesome areas daily using portable monitoring equipment. Geophones were placed in special drill holes along the roof and walls of the sublevels. Monitoring was carried out at 20-minute intervals at each location during quiet times. The data was tabulated, and daily plots of microseismic rate were kept current for each sublevel. A plot from some of these data is shown in figure 7-1. The high initial microseismic rate reflects the general instability of the sublevel roof. To stabilize the roof, a recommended program of reinforcement, using 10-ft fully-grouted rebars, was completed. The effectiveness of this reinforcement was soon apparent, as the high microseismic rates almost immediately decreased to a stable background rate.

Rock Burst Monitoring

Rock bursting is a major hazard in some deep mines. In addition, the resulting loss of production and expense of clean-up and repair make rock bursting a severe operational problem. The problem becomes more critical as mines go deeper.
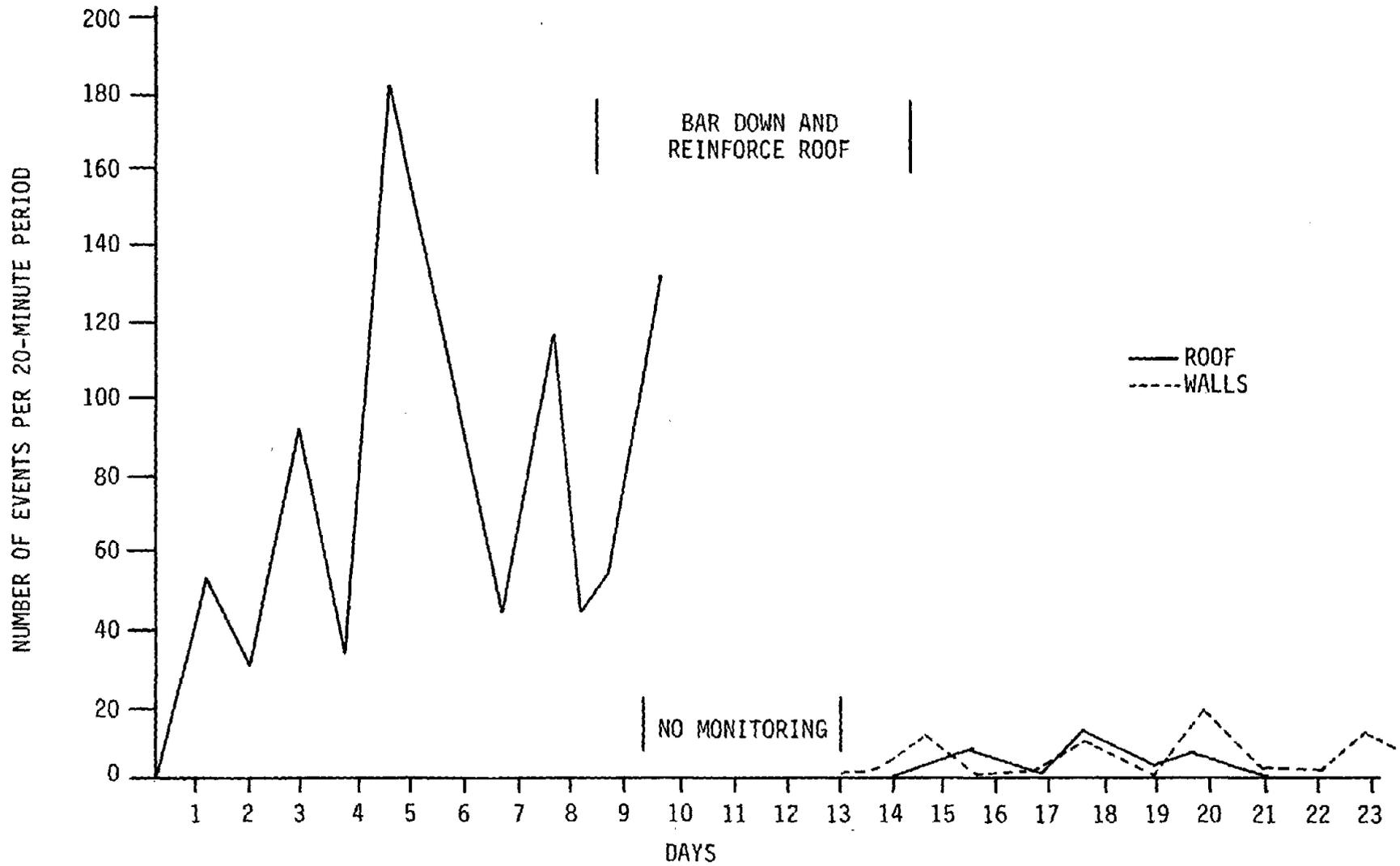
FIGURE 7-1— MICROSEISMIC DATA FROM FIRST SUBLEVEL SAN DIEGO MINE [after (1)]

One rock burst control technique used in the Coeur d'Alene
mining district of northern Idaho is a combination of minewide
microseismic monitoring and destress blasting. Burst-prone areas,
primarily pillars, are delineated by monitoring. They are then
destressed by drilling and blasting.

Previous monitoring of burst-prone structures has shown
that when a pillar is reduced to 40-60 ft in thickness it reaches
a critical burst-geometry. The microseismic rate increases signi-
ficantly, and most of the noise is generated within the pillar.
Also, substantial increases in seismic velocities, measured by
surrounding geophones, indicate a general stress increase in the
pillar area. A gradually failing pillar, which is also micro-
seismically noisy, is characterized by decreasing seismic velo-
cities.

Another example of using microseismic monitoring to improve
rock burst control is taken from studies carried out at ASARCO's
Galena mine (2). The geophone array used to monitor a burst-
prone pillar is shown in figure 7-2. Source locations for the
first few months of monitoring, which began in November 1969,
are shown on figure 7-3. Data indicated that mining had not yet
created a critical burst-geometry of the pillar. Initial mining
of the next cut suddenly shifted the stress up into the pillar,
as shown by the source-location plots in figure 7-4. The accom-
panying increase in seismic velocity, registered by surrounding
geophones, is apparent in Table 7-1.

Table 7-1. - Seismic Velocities, 40-135 stope

Geophone	Feb. 2, 1970 velocity, fps	Mar. 4, 1970 velocity, fps
1	19,699	20,101
2	18,403	20,406
3	19,397	20,519
4	--	20,221
5	20,419	21,325
6	20,424	20,535
7	Shot Time	Shot Time

This data indicated a burst could be expected. However,
buildup of stress was so rapid there was no time to destress.
The next afternoon miners were removed from the stope when it
became very active, both microseismically and seismically. The
following morning a small burst occurred in the back end of the
stope pillar.
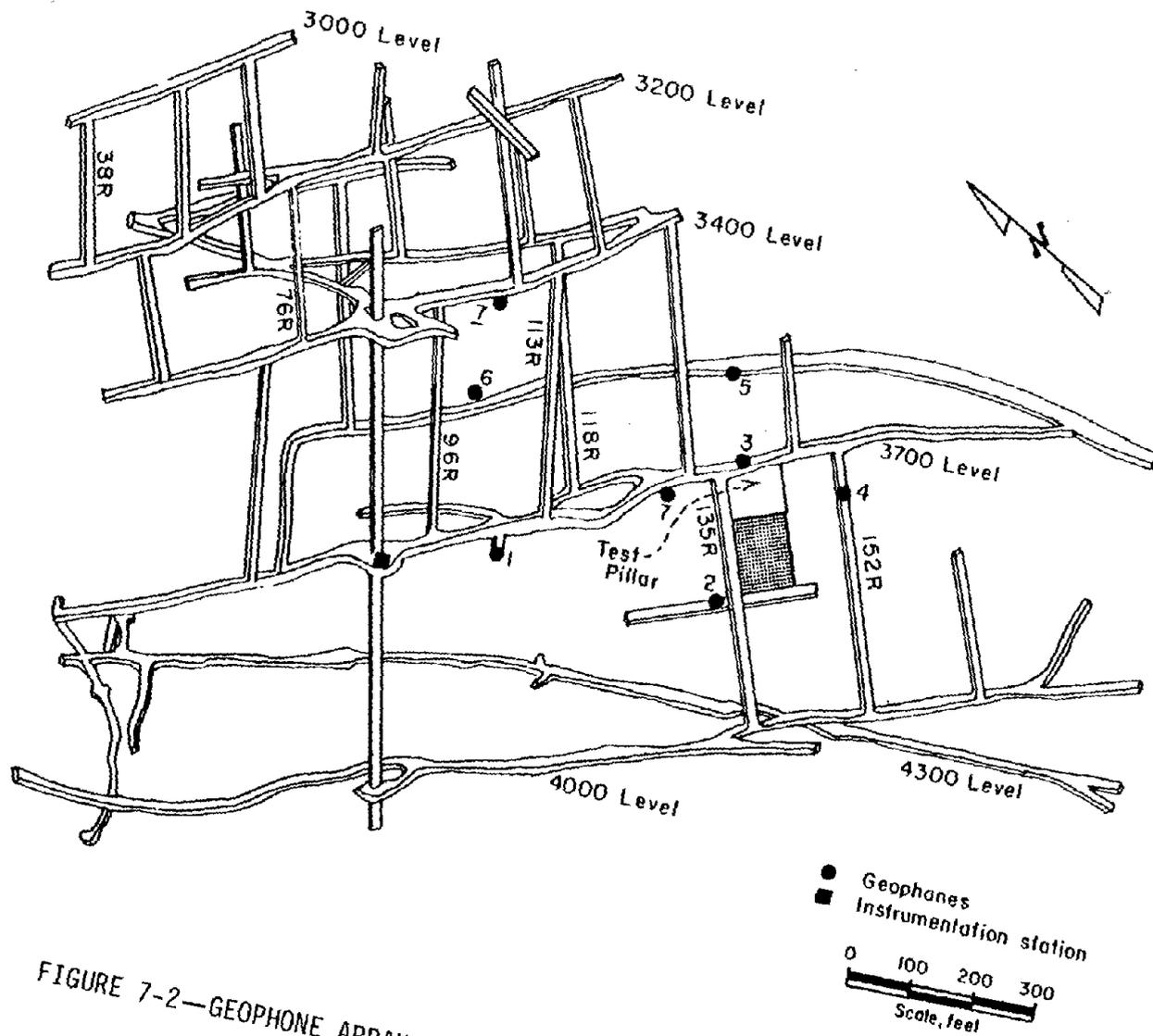
FIGURE 7-2—GEOPHONE ARRAY TO MONITOR BURST-PRONE PILLAR (2)
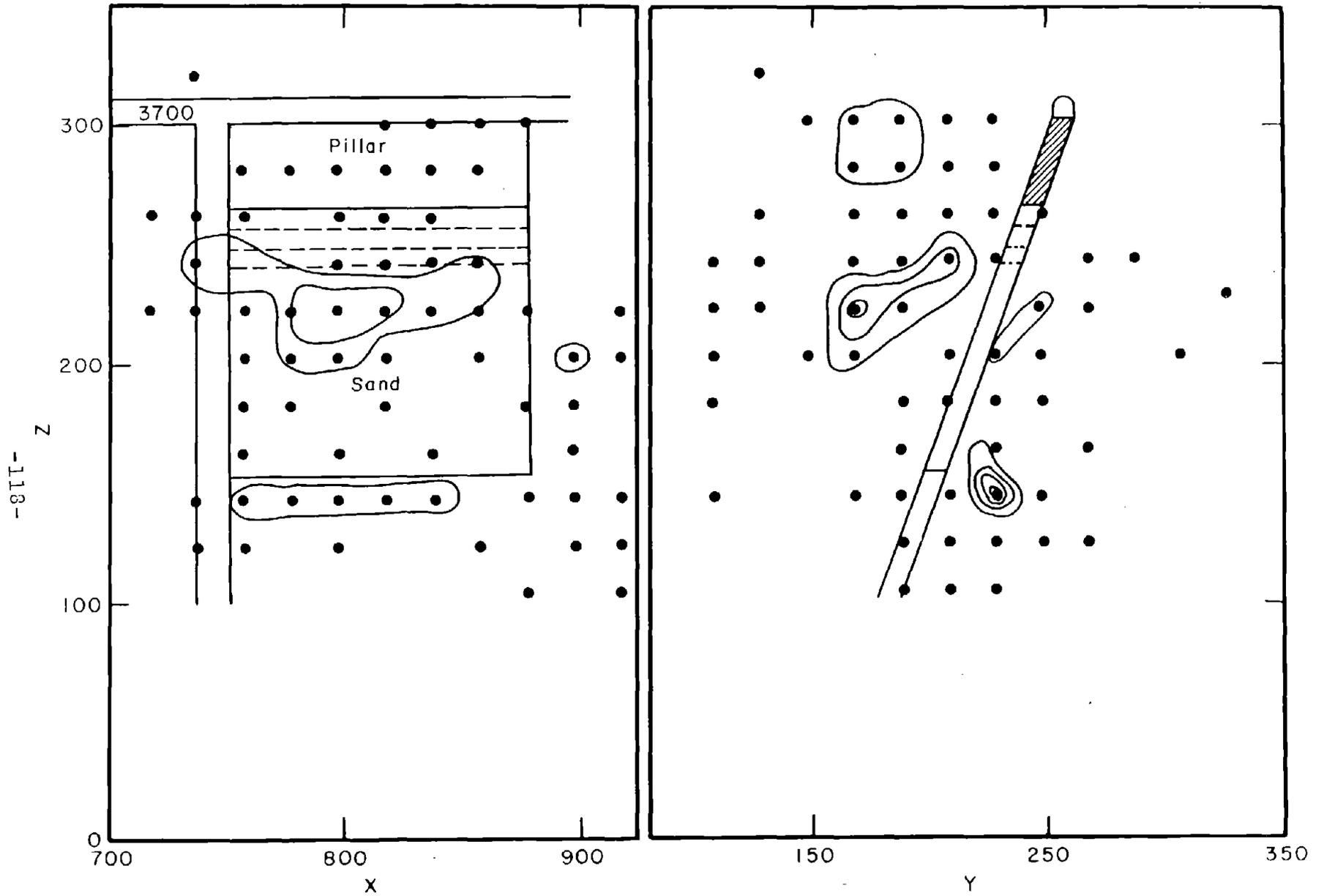
FIGURE 7-3— ROCK NOISE SOURCE LOCATIONS, NOVEMBER 1969-FEBRUARY 1970,
40-135E STOPE, WITH RELATIVE INTENSITY CONTOURS (2)

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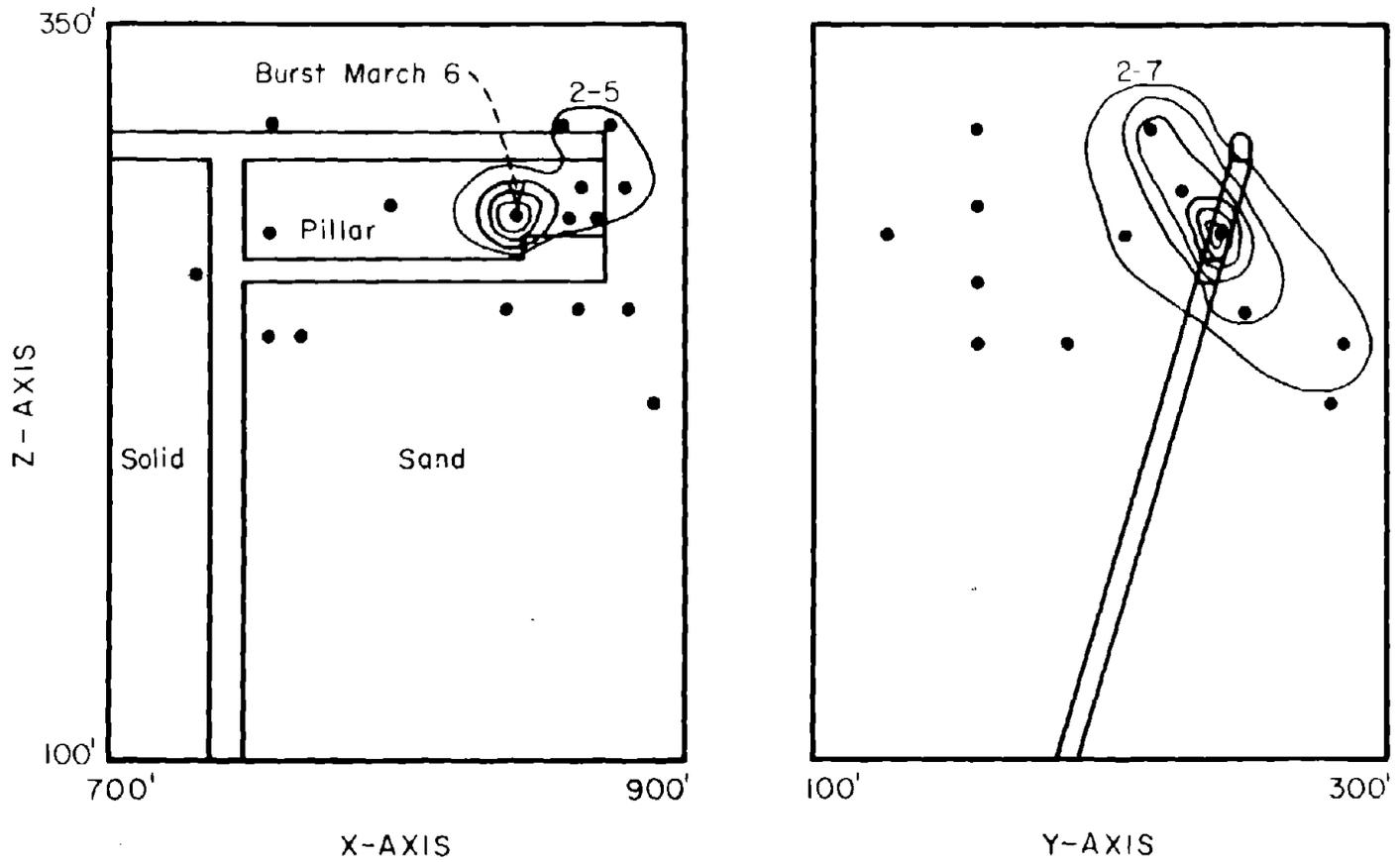
FIGURE 7-4— ROCK NOISE SOURCE LOCATIONS, MARCH 4, 1970, 40-135E STOPE
WITH RELATIVE INTENSITY CONTOURS (2)

Mining resumed after a short period of cleanup and repair.
Continued microseismic monitoring indicated the pillar was still
burst prone, as can be seen from the data in figure 7-5. The
remaining pillar was destressed by blasting a series of 20-ft
long holes drilled on 5-ft centers.

Microseismic monitoring and seismic velocity surveys through
the pillar were used to verify the effectiveness of destressing.
Figure 7-6 shows the results of the seismic velocity surveys.
The significant reduction in seismic velocity throughout the
pillar indicated the pillar had been fractured and softened, hence
was presumed to be destressed. No further bumping or bursting
occurred as the stope pillar was mined out. Microseismic activity
remained low and was confined to the walls around the stope.

This example illustrates the usefulness of microseismic moni-
toring in recognizing a problem and in evaluating remedial action.
It also shows that sometimes microseismic buildups occur so rapid-
ly there is only time for removal of workers from the area.
Though this is standard practice, in most cases bursting does not
occur following the buildup. When the stope or working area has
settled down microseismically, usually the next day, work is re-
sumed under close scrutiny of the on-line microseismic monitoring.

Coal Bump/Bounce Monitoring

Microseismic monitoring of bump or bounce-prone areas in coal
mines is very similar to rock burst monitoring. An array of geo-
phones is installed to monitor minewide or a specific area. Add-
ed operational problems in coal mines are equipment permissibility
requirements and the fast-changing mining geometry due to rapid
extraction of coal. A description of one monitoring project in
a deep Colorado mine is taken from a Bureau of Mines study (3).

Each specific study area was covered by 7 geophones. Data
from the preamplified geophone output was cabled to a monitoring
facility on surface, recorded on magnetic tape, and processed by
an automatic arrival-time unit.

Normal mining in stable areas produced a low, steady back-
ground microseismic rate of some 10 events per day. Mining into
unstable areas caused a dramatic increase in the microseismic
rate, as shown in figure 7-7. A fault that crossed through the
mining area apparently created a stress imbalance in the barrier
pillar. Figure 7-8 is a time sequence plot of cumulative source
locations. It clearly indicates that stress increased along the
fault and concentrated in the barrier pillar as mining continu-
ously shifted more load onto the pillar. As a result of this
project a better mine layout and mining sequence was established
to minimize bumping.

This example illustrates the usefulness of microseismic
monitoring and the importance of taking into account the local
geologic and structural conditions. The importance of combining
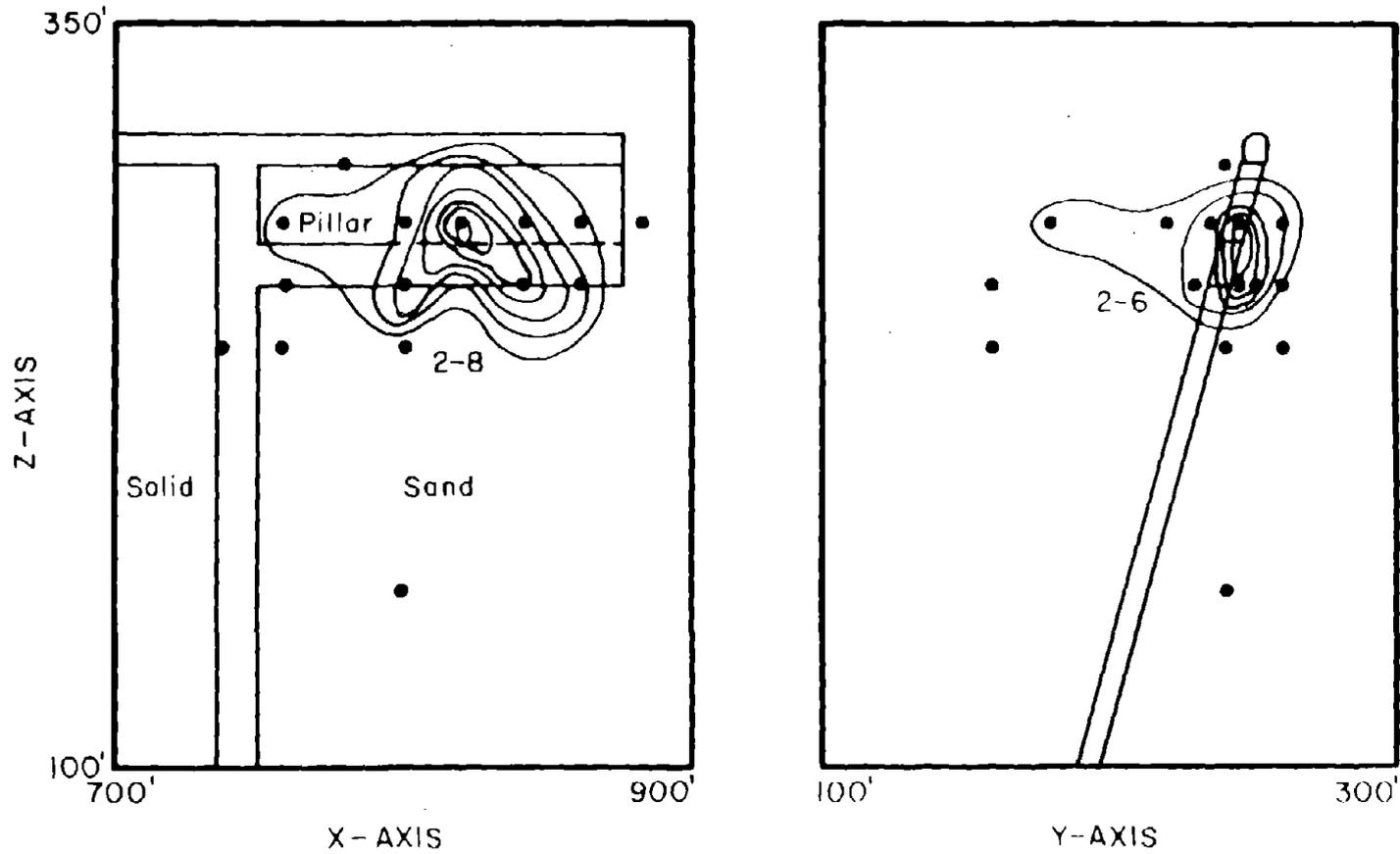
FIGURE 7-5— ROCK NOISE SOURCE LOCATIONS, APRIL 15-16, 1970, 40-135 E STOPE,
WITH RELATIVE INTENSITY CONTOURS (2)
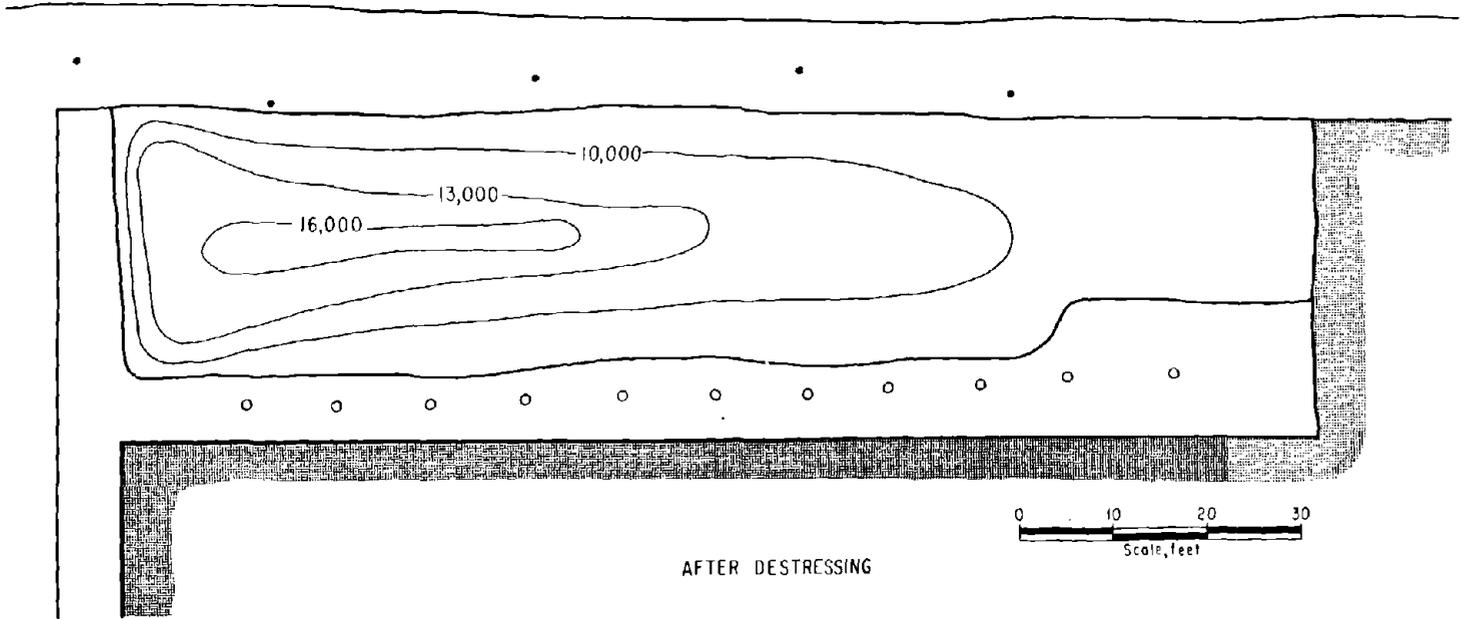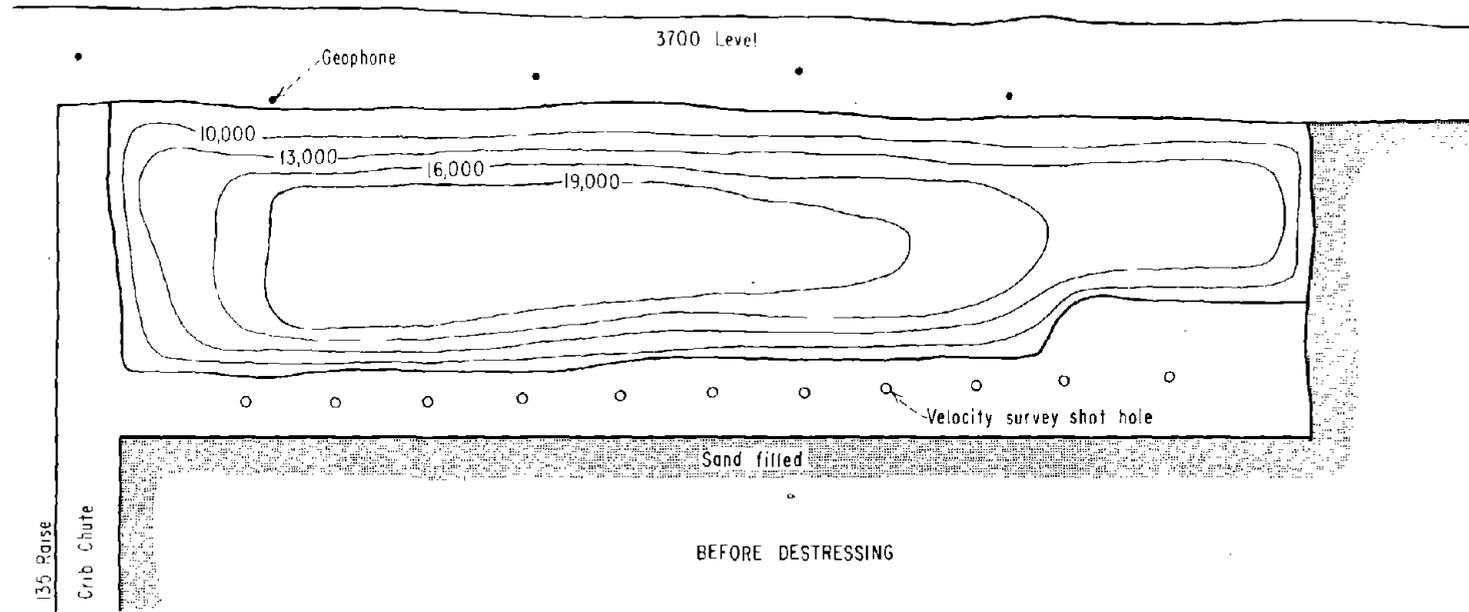
FIGURE 7-6— CONTOUR PLOTS OF SEISMIC VELOCITIES, fps, 40-135   E STOPE PILLAR (2)
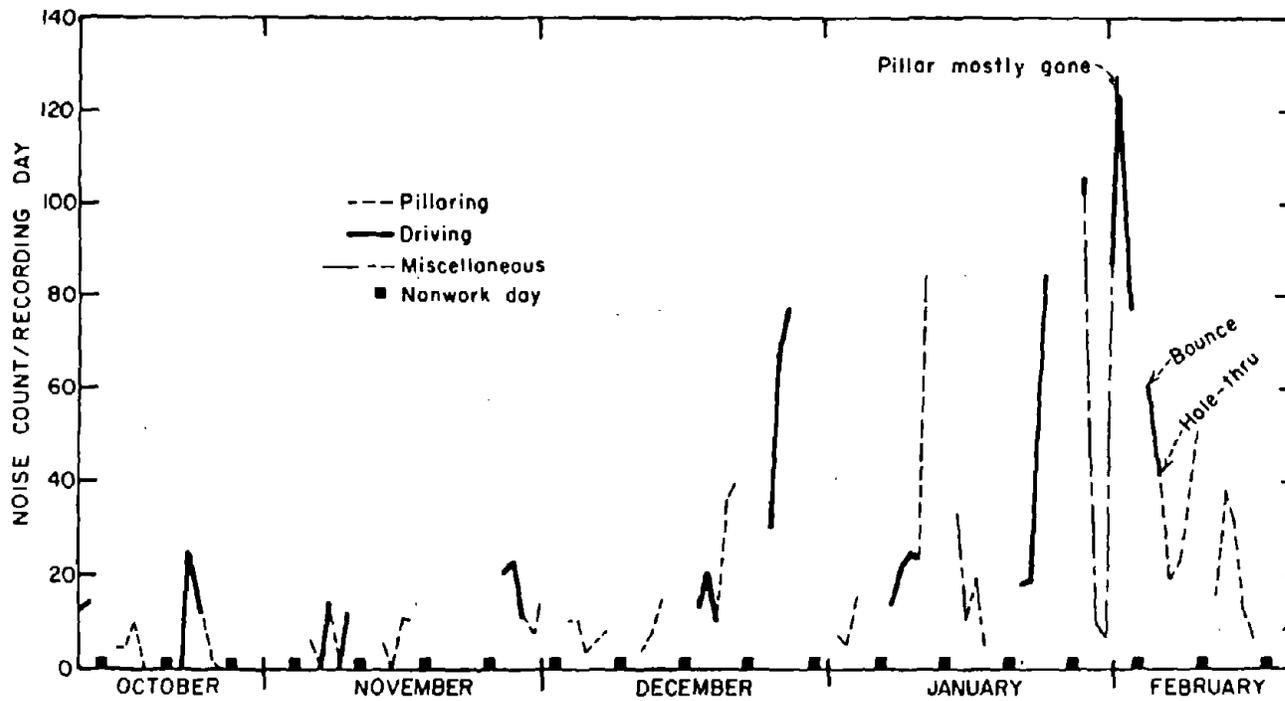
FIGURE 7-7— ROCK NOISE RATE PLOT 3rd SOUTH WORKING AREA OCTOBER 12, 1972 to FEBRUARY 20, 1973 (3)
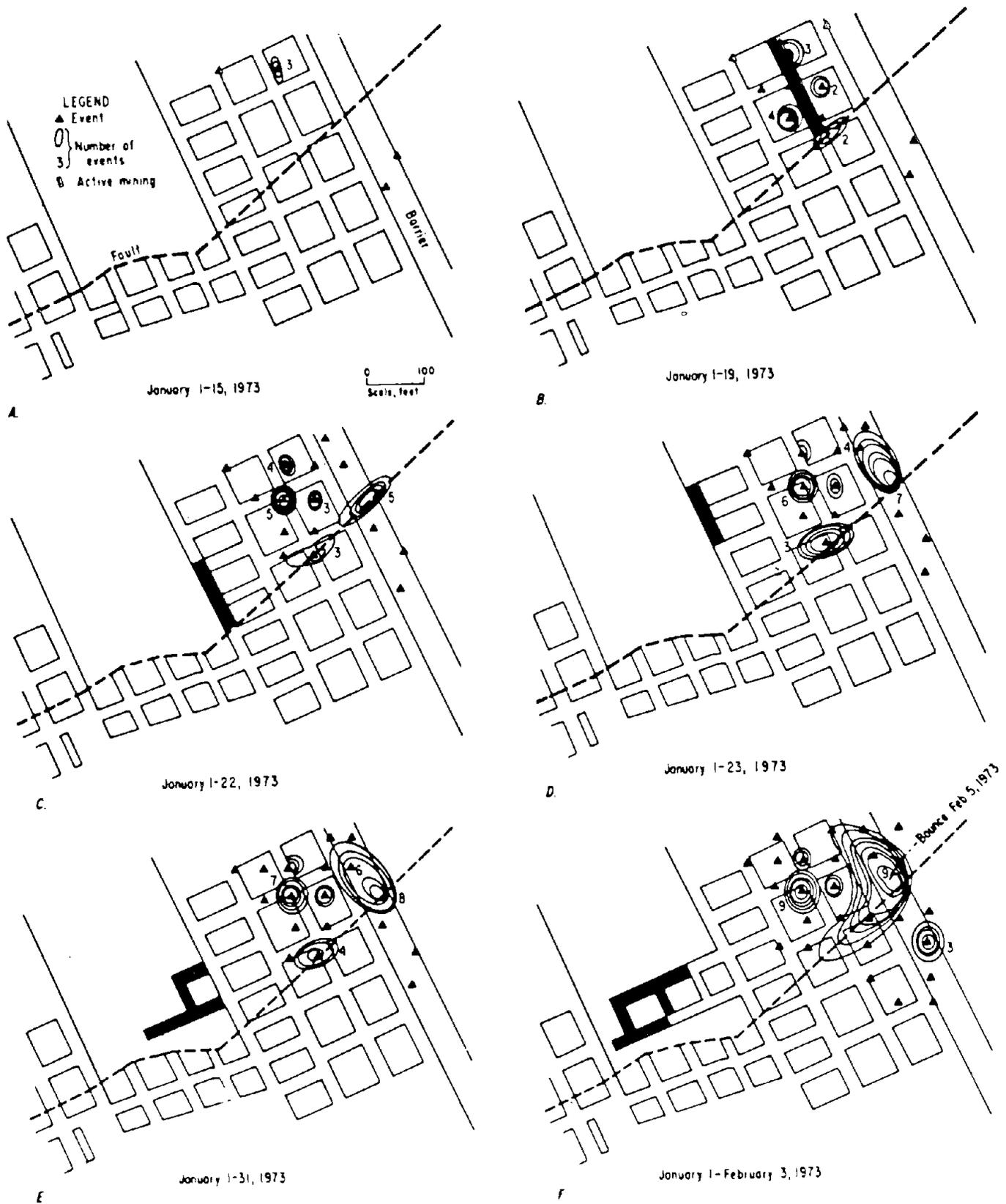
FIGURE 7-8— CUMULATIVE SOURCE LOCATIONS PRECEDING COAL MINE BOUNCE, 3rd SOUTH (3)

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the microseismic data with the mining, the geologic and rock mechanics data cannot be overemphasized.

Short-Period Seismic Monitoring

Monitoring rock burst-prone mines with short-period seismic systems (seismographs) began in the Kolar Gold Field of India in 1912. Similar monitoring was initiated in South Africa in the 1930's and in the Coeur d'Alenes in 1966. Short-period seismic arrays to monitor coal bumps have been used in the U. S. since the early 1960's and in Europe since the mid-1960's. The purpose of short-period seismic monitoring is to provide a record of all rock bursts or coal bumps and a means of categorizing the size of such events based on instrument response rather than on observations or damage reports.

In India, the Kolar Gold Field Observatory classified all bursts detected according to displacements of the recording stylus. Bursts producing displacements greater than 2 mm were considered large. The intent was to use the compiled burst data in evaluating changes in mining methods with respect to bursting. However, too many mines with too many changing variables precluded meaningful evaluations.

In South Africa short-period seismic monitoring has been used primarily to relate overall release of seismic energy to reef closure at a mine. The purpose is to determine which mining rates release the least amount of seismic energy. A more recent application is evaluating the use of large stabilizing pillars to minimize stress buildups and resulting rock bursts. A reduction in released seismic energy, detected by the short-period monitoring system, will indicate that the stabilizing pillars are effective.

A short-period seismic monitoring system is being used at each major mine in the Coeur d'Alene Mining District (4). These systems, which provide a record of all bursting and large seismic events occurring at a mine, are invaluable in supplementing the microseismic systems. In addition, they encourage better reporting of suspicious bumps or heavy-ground movement felt by underground personnel.

Short-period seismic systems in coal mining areas are used primarily to report coal bumps. Efforts have been made to determine the source of the bumps, then relate the bumping to mining or geologic structure. However, the time resolution on the recorded seismograms is inadequate for accurate source location.

Surface Monitoring

The California Department of Transportation has routinely used microseismic monitoring to evaluate the stability of highway cuts and old landslides intersected by a highway. A typical example of one of their monitoring jobs is presented in the following case history (5).

A new highway was under construction some 300 feet below the existing road. The natural slopes in the weathered granitic rock were as steep as 1.2:1. In July of 1973, cracks were noted above a 135 ft high 0.6:1 cut that was nearing completion. A mobile microseismic monitoring van and crew were dispatched to the site to examine the problem.

Examination of the slope by an engineering geologist revealed an extensive area of surface cracking above the new road, and a fault running from the top of the cut down under the new road, as shown in figure 7-9. Monitoring began immediately from geophone locations on the slope, as also shown on this figure. All geophones were buried in shallow, augered holes to minimize extraneous surface and construction noise, and to get good contact with the slope material. Monitoring was carried out twice daily for 15 minute recording periods. The microseismic data for the geophones in the upper part of the slope near the cracks were low. However, microseismic rates for the geophones located at C and D, near the fault, were high and increasing, as shown in figure 7-10.

The microseismic data, coupled with some displacement data taken from the slope, indicated that remedial measures were necessary. In accordance with recommendations, a buttress was constructed at the base of the cut slope as quickly as possible. As can be seen from the data on figure 7-10 the microseismic rate rapidly decreased as the buttress became effective.

The microseismic monitoring provided an almost immediate evaluation of slope stability that proved to be both diagnostic and accurate. It also provided a record of the stability of the stope before, during and after corrective measures.

Specialty Monitoring

The ability to locate the source of an event by the arrival-time-difference method has led to a number of specialty monitoring applications. Microseismic monitoring is now being applied to mapping the propagation and extent of hydrofracturing (6),determining an advancing cave line (7), determining the stability of underground petroleum or gas storage reservoirs (8), determining the stability of nuclear waste respository excavation (9), and locating trapped miners (10).

Monitoring procedures may differ from the more traditional geotechnical applications, in that the signal may be of lower amplitude and frequency. This usually requires more sophisticated filtering to improve the signal-to-noise ratio, and may require digital processing and data analysis to isolate the signal from background noise. Geophones may have to be mounted in deep holes to get closer to the source and to eliminate background surface noise.

● GEOPHONE LOCATION

Scale
0 _____ 100 ft.

2500

● B

EXISTING   ROAD

● A

2400

N

2300

SURFACE
CRACKS

● F

TOP OF CUT

● E   2200   D →   SLIP PLANE   ● C

Sta. 2198

NEW   HIGHWAY

2100
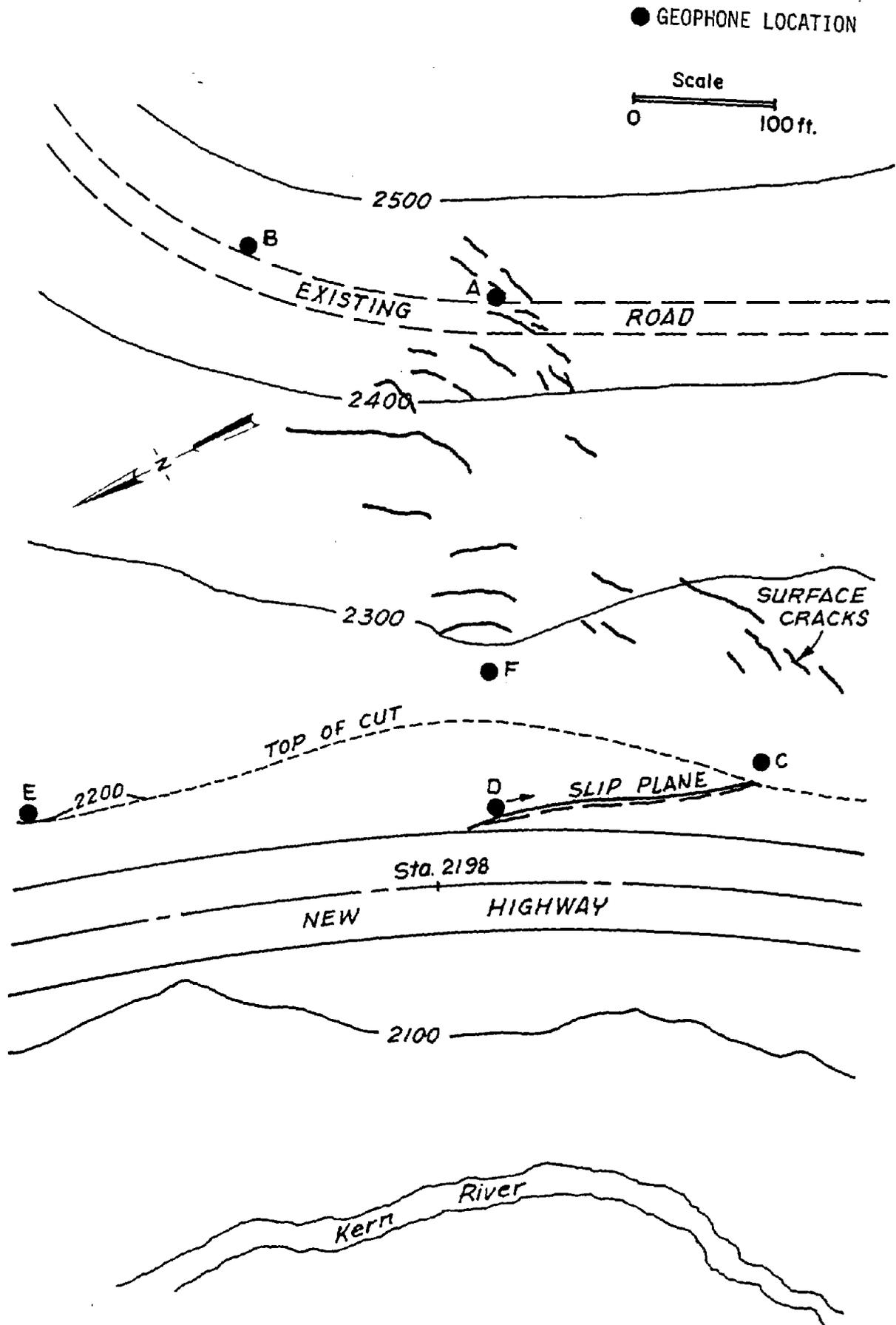
Kern   River

FIGURE 7-9— DETAILS OF KERN RIVER CANYON FIELD SITE (5)
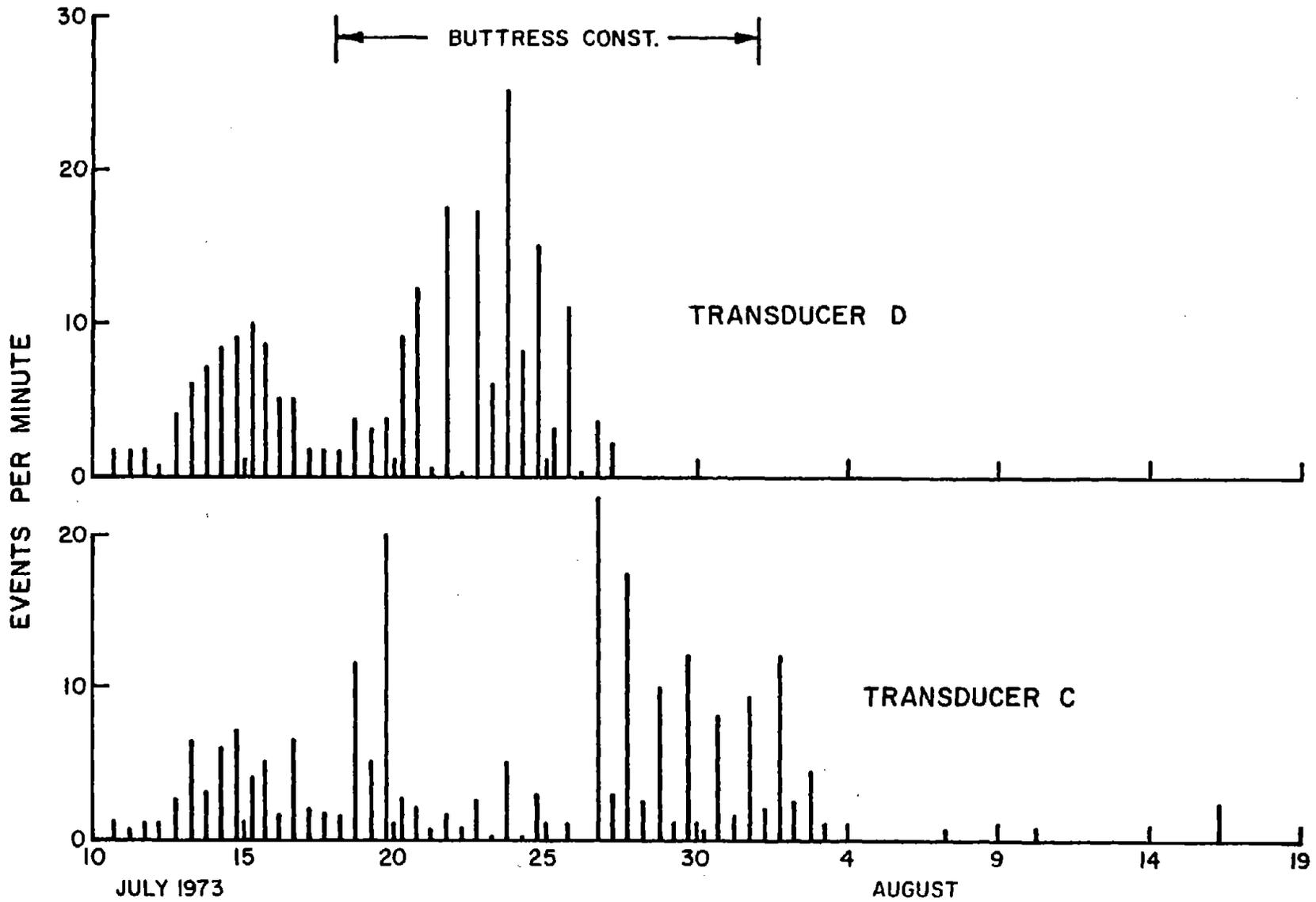
FIGURE 7-10— NOISE RATES MONITORED ON GEOPHONES C & D KERN RIVER FIELD SITE (5)

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APPENDIX A.- GEOPHONE PICKUP DETERMINATION

From the manufacturer's specifications regarding gage sensitivities and frequency response, one can compare velocity and acceleration gages to determine which is the more sensitive over a given frequency range. We calculate the crossover frequency or the frequency at which each type of geophone is equally sensitive.

At this crossover frequency the output voltage of the two types of gages must be equal; hence,

$$E_a = ak_a = E_v = vk_v, \qquad (A-1)$$

where

E_a is accelerometer output voltage,
E_v is velocity gage output voltage,
a is particle acceleration,
v is particle velocity,
k_a is accelerometer sensitivity (volts/g), and
k_v is velocity gage sensitivity (volts/in/sec).

Since $a = 2\pi fv$, we can substitute into equation A-1 to obtain

$$2\pi fvk_a = vk_v$$

or

$$f = \frac{k_v}{2\pi k_a} \qquad (A-2)$$

where f is the desired crossover frequency.

The following example will illustrate the use of equation A-2 in selecting the proper type of geophone:

To choose between a velocity gage of 1.0-volts/in/sec sensitivity and an accelerometer of 0.35 v/g sensitivity for a study where low stress levels will be encountered

$$f = \frac{1.0 \text{ volts/in/sec}}{2\pi \times 0.35 \text{ volts/g} \times \dfrac{1 \text{ g}}{32.2 \text{ ft/sec}} \times \dfrac{1\text{ft}}{12\text{-in}}} = 176 \text{ Hz.}$$

Hence, if the characteristic frequencies of rock noises generated were less than 176 Hz, the velocity gage would be more sensitive and would be used. Similarly, if the predominant frequencies were greater than 176 Hz, the accelerometer would be more sensitive and thus selected. It should be mentioned, however, that the crossover frequency must lie within the limits of the flat frequency response of the gage.

APPENDIX B. - MICROSEISMIC AMPLIFIERS

Although some seismic exploration work with velocity gages is accomplished without amplifiers, virtually all microseismic installations use a preamplifier located at the geophone. In the case of velocity gages, a preamplifier is needed because the output is so small the signal will be lost in extraneous noise picked up by the cable. The noise problems with the accelerometer is worse because of its high impedance and low level output. Any long cable will noticeably attenuate its output.
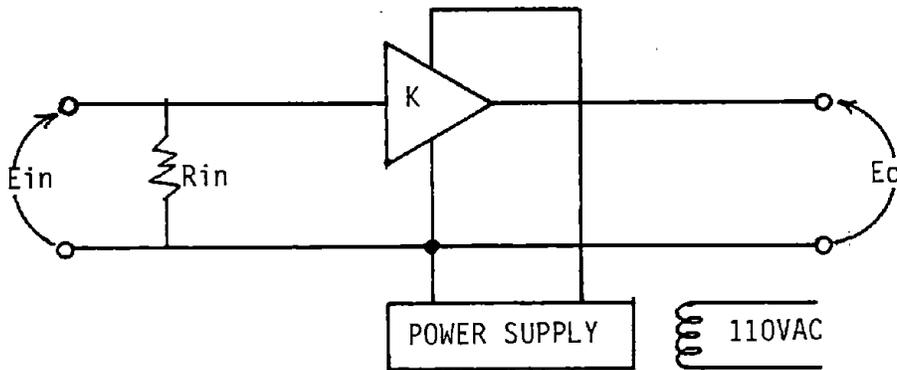
FIGURE B-1—UNBALANCED AMPLIFIER

Figure B-1 represents a model of an unbalanced, or single-ended amplifier. Both its input and output share a common conductor. The gain of the amplifier is defined as the ratio of output voltage to input voltage. Gain may be expressed either as a voltage ratio, without units, or as gain in db, defined as:

$$\text{db gain} = 20 \ \text{LOG}_{10} \ \frac{Eo}{Ein}$$

The amplifier shown is assumed to have very low output impedance, and is unaffected by normal loading. The amplifier input resistance is represented by R_{in}.

For the purpose of microseismic instrumentation, the effects of noise generated by the transducer amplifier must be considered. In figure B-2 noise generators have been added to the amplifier to represent noise sources. The two noise generators are equivalents for random noise generated by the various noise sources in a transistor amplifier.
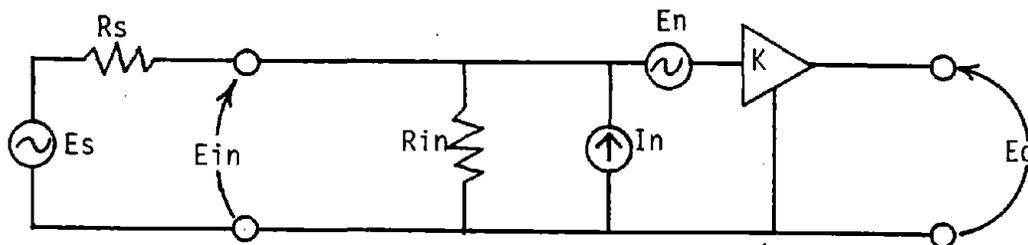
FIGURE B-2—GEOPHONE AMPLIFIER WITH NOISE SOURCES

The amplifier model in figure B-2 has became an industry standard for audio frequency amplifiers. The noise parameters, E_n and I_n, are specified for most devices intended for low level instrumentation. E_n and I_n are expressed in terms of voltage and current per $(Hz)^{1/2}$. On occasion they are expressed in terms of $volts^2$ and $amps^2$ per unit frequency. This means of expression is necessary because the noise power is distributed over a broad frequency range. The noise power emitted is dependent on the bandwidth over which it is measured. Thus the published noise parameters for a device are for a one Hertz bandwidth. If the system bandwidth is 10KHz, and E_n and I_n are constant with respect to frequency, the published E_n and I_n values must be multiplied by $(10,000)^{1/2}$ to obtain the actual contribution of the two noise generators.

Typical noise parameters for commercially available devices are listed:

	E_n	I_n
Bipolar Amplifier	3.0 nV/Hz$^{1/2}$	0.1 pA/Hz$^{1/2}$
FET amplifier	8.0 nV/Hz$^{1/2}$	3.0 fA/Hz$^{1/2}$

An inpsection of figure B-2 reveals that the source resistance, R_s, determines which noise generator is the dominant noise contributor. If R_s is very small, the voltage generated by current I_n through R_s will be much smaller than E_n. Thus E_n is dominant. Likewise, if R_s is very large, as is the case with a high impedance tranducer, I_n will generate a larger voltage than E_n and I_n determines the noise characteristics of the amplifier.

Transducer selection is usually dictated by sensitivity and cost. The amplifier is made to match the transducer. The FET amplifier will produce less noise with high impedance transducers, such as the accelerometer. (Piezoelectric being the only accelerometer type considered here). Similarly, the

bipolar amplifier will be less noisy with the low impedance transducers such as the velocity gage.

When one amplifier is to be used with both velocity gages and accelerometers, the FET amplifier should be used since it offers higher impedance and only about twice the noise of the bipolar amplifier. However, bipolar amplifiers will be about 10 times noisier than the FET amplifier when used with an accelerometer.

The amplifier equivalent-noise sources, E_n and I_n, have a limited frequency range over which they exhibit their lowest values. Figure B-3 shows the noise characteristics for a typical audio amplifier.
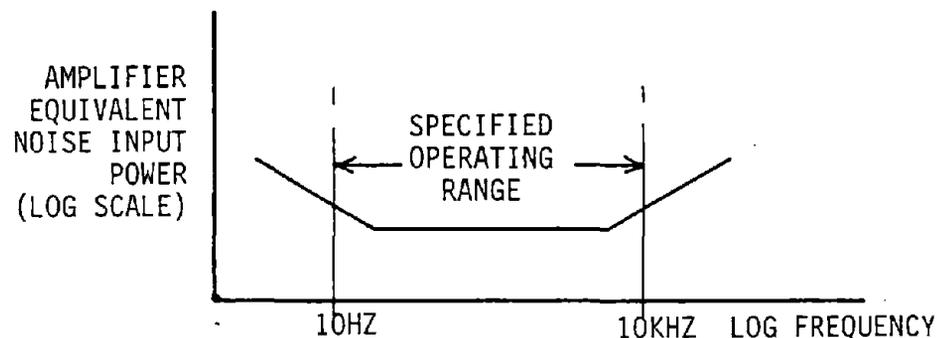
FIGURE B-3—FREQUENCY DEPENDENCE OF I_n AND E_n FOR A TYPICAL AMPLIFIER

Before any amplifier is considered for an application, the noise-source frequency dependence should be ascertained. An amplifier can have a good noise performance, but the bandwidth over which the specification holds may be restricted. The low frequency limit is a highly variable number depending on the type of amplifier. For microseismic applications a lower-limit noise figure approaching 10Hz is obtainable. Velocity gages and piezoelectric accelerometers are electrical generating transducers. That is, for given amount of particle motion, they generate a given amount of electrical power. The transducer signal power (coupled to the amplifier), compared to the amplifier's own equivalent noise power, defines the system signal-to-noise ratio. Figure B-4 compares the power frequency response for a velocity gage and an accelerometer.
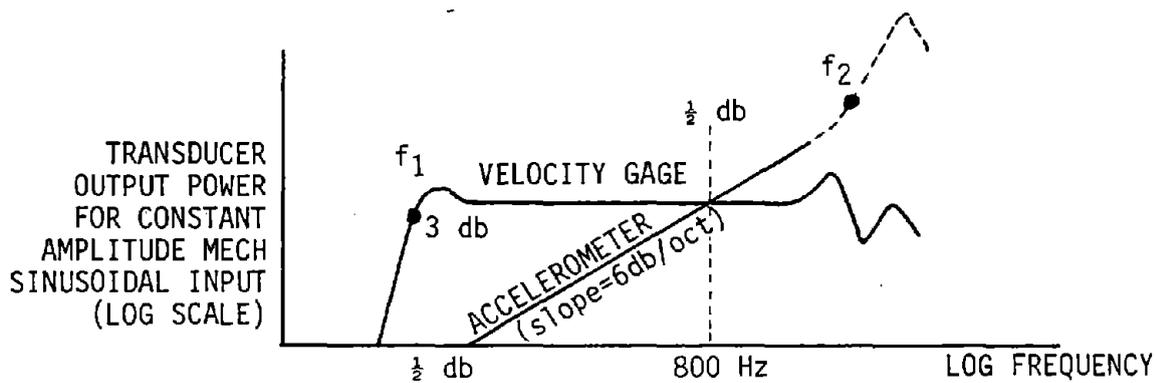
FIGURE B-4—FREQUENCY RESPONSE FOR TYPICAL TRANSDUCERS

The velocity gage has a fairly constant output over its useful bandwidth. The lower cutoff frequency f_1 for the gage is determined by the seismic-mass suspension-system mechanical resonance. Most manufacturers define f_1 as the frequency where the response is 3 db below the mid-frequency response. Velocity gages will often show a response resonant peak near f_1. This is due to the gage having insufficient internal damping. Damping can be increased to eliminate the resonant peak by adding external shunt resistance to the output terminals. Most manufacturers specify this resistance.

Critical damping of velocity gages is advantageous. Most velocity gages are resonant below 15Hz. Signal components in this frequency region contribute little to arrival-time information; large amplitude, low frequency signals can interfere with event recovery by overloading the amplifier.

The upper frequency limit for the velocity gage is determined primarily by parasitic mechanical resonances in the gage, and its mounting. The frequency response of the velocity gage (figure B-4) becomes very ragged above about 2KHz. Since these variations in response are usually quite large, a means should be provided to cut off all frequencies outside the gage's normal operating range.

The accelerometer response in figure B-4, is expressed in terms of constant velocity input and shows a voltage response which is proportional to frequency. The high frequency cutoff, f_2, of the accelerometer (figure B-4) is primarily determined by the resonant frequency of the piezoelectric crystal and its seismic mass. Accelerometer mounting has an effect on f_2. As resonant frequency is approached, the response becomes very irregular. A means should be provided in the system to eliminate frequency components outside the accelerometer's normal operating range.

Transducer output power is plotted in figure B-4 instead of transducer output voltage. Available power is defined as

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that signal power which would flow from the transducer to the amp-
lifier when their impedance are optimumly matched. It can be seen
that above 800 Hz the accelerometer is delivering more power
to the amplifier than is the velocity gage. In this case of
impedance matching, the accelerometer has a noise performance
advantage over the velocity gage above 800 Hz. In practice,
impedance matching between the amplifier and transducer is
not economically possible. The result is a slight increase
in the frequency at which the accelerometer demonstrates a
noise performance advantage.

The lower cutoff frequency, f_1, for the accelerometer is
primarily determined by the amplifier input resistance, R_i,
the combined capacitance of the accelerometer, and the cable
connecting the accelerometer to the amplifier. The cable
capacitance may be larger than the accelerometer capacitance.
The signal voltage generated by the accelerometer is attenu-
ated by the cable capacitance. Thus cable capacitance can be
the determining factor in both system sensitivity and low
frequency cutoff.

There is a convenient technique for eliminating this
capacitance problem. A feedback capacitor is added to the
FET amplifier.
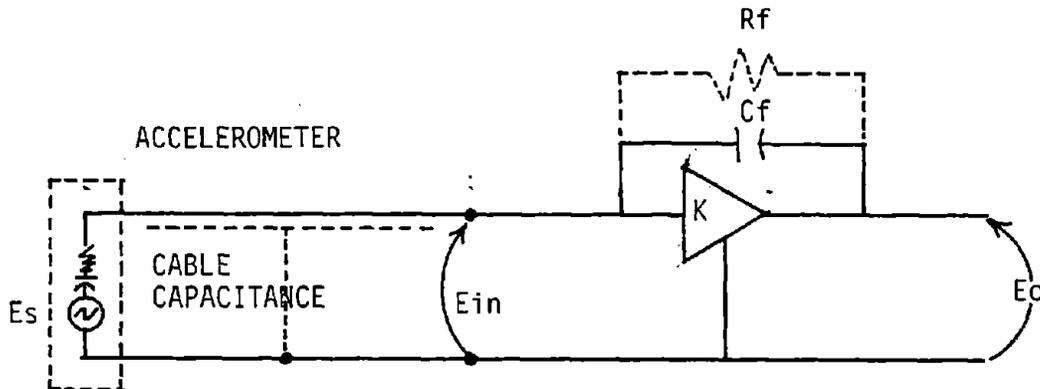
FIGURE B-5—CHARGE AMPLIFIER

In the amplifier shown in figure B-5, if the gain, K, is
made very large, the circuit functions as a charge-to-voltage
converter, thus its name "charge amplifier". The amplifier
feedback action is such that the amplifier will attempt to
keep voltage, E_{in}, at zero by feeding charge back through capa-
citor C_f. In so doing the amplifier will develop a voltage
across the capacitor determined by the capacitance law:

$$\text{Capacitance voltage} = \frac{\text{input charge}}{C_f}.$$

Since E_{in} is small, the voltage across the capacitor is nearly equal to the amplifier output voltage, E_O. The gain for the amplifier is $1/C_f$ volts per coulomb.

The cable capacitance no longer determines the system gain or the low-frequency cutoff point. Furthermore, the noise performance of the amplifier is not degraded by the feedback capacitor. The capacitance should be chosen so that the amplifier gain is not so reduced that succeeding cables and further amplification begin to contribute noise.

As a practical necessity some means of supplying bias current to the amplifier is necessary. Otherwise the amplifier will gradually drift off scale as leakage charge accumulates on C_f. The feedback resistor R_f provides a path for the bias current. R_f also determines the low frequency cutoff point f_1, just as resistor R_{in} limits the low frequency response of the accelerometer FET amplifier without feedback.

An accelerometer is a high-impedance, low output device. A charge can be generated when the signal cable is flexed. This effect can be very troublesome unless special low capacitance cables that are rated for accelerometer service are used.

Most commercially available preamplifiers suitable for microseismic application do not have self-contained power supplies. In some installations battery power is used, but most systems use centrally located line operated power supplies to serve several preamplifiers. Power is supplied to each preamplifier through a dedicated pair of wires in the geophone cable. The amplifier signal output is carried on an additional pair of wires or a single additional wire, with the power common used as the signal return.

The selection of preamplifier gain is influenced by several factors. To provide the best signal-to-noise ratio, all of the system gain should be located as close to the transducer as possible. In this way a high signal-to-noise ratio is established before transmission.

For systems with a threshold detector on each channel, preamplifier gain determination is simple. The preamplifier gain is selected so that the smallest event of interest will generate a signal. For a threshold level of 1 volt and a velocity gage with a sensitivity of 1 v/in/sec, a minimum detectable event is of 0.0005 in/sec and will require a gain of 2000 (66db).

For an accelerometer the gain requirement in the above example is determined using the following relationship:

$$\text{acceleration} = 2\pi f \text{ velocity, in consistent units.}$$

At 1000 Hz, the acceleration would be

$$2 \, \pi \, 100 \times 0.0005 = \pi \text{ in/sec}^2$$

or in g's, the acceleration is

$$\pi \, / (32.2 \times 12) = 8.13 \text{ mg.}$$

For an accelerometer with a sensitivity of 300 mv/g, the accelerometer voltage output would be

$$(8.13 \text{ mg}) \times (300 \text{mv/g}) = 2.44 \text{ mv}$$

and with a voltage amplifier, the required gain for a 1 volt output is just

$$1/(2.44 \text{mv}) = 410 \text{ (52.2 db).}$$

Some difficulty with this scheme may arise if the amplifiers do not have good overload recovery characteristics. The gain chosen can easily cause amplifier overload, since many events will be much larger than the minimum assumed here. If the amplifier maximum output voltage swing is 10 volts, an event only 10 times the minimum detectable will cause amplifier overload.

Microseismic Cable Considerations

In most installations the transducer array is distant from the dataprocessor. Typical cable runs are about 5000 ft for an underground installation. A number of transmission means including wireless and fiber optic have been proposed, but at present metallic electrical cable is most economical.

Signal attenuation in cable is usually not much of a problem. For instance the attenuation of a 10,000 ft cable with 20 gage conductors is only a few db in the low audio-frequency range. Some manufacturers provide a means of inserting a calibration signal at the transducer amplifier to permit measurement of overall system gain. One system has been constructed that allows injection of a calibration signal at the data processor. The calibration signal is transmitted via cable to the transducer amplifier calibration input, then returned for verification.

The microseismic user has two frequent problems, cable noise pickup and maintenance. The electrical power distribution system is the source of most interference. It is the source of low-frequency noise (harmonics of the line current fundamental frequency) as well as transient mine-power switching noise.

The power system noise is transmitted to the microseismic cables by three mechanisms, magnetic and capacitance coupling and redundant grounds. Capacitive coupling is illustrated in figure B-6 below. The principal cause is running signal cables near mine-power cables.
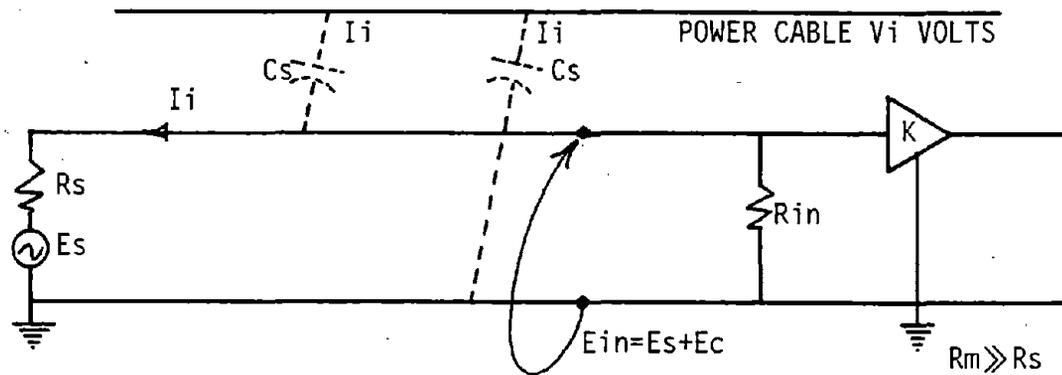
FIGURE B-6—MICROSEISMIC CABLE CAPACITIVELY COUPLED TO HV POWER CABLE

The signal wire in figure B-6 connecting the transducer to the amplifier is assumed to be a twisted pair cable, and the power cable nearby is carrying AC current. This causes capacitive coupling between each signal wire and the power cable. The capacitances, C_s, linking each signal wire to the power cable are approximately equal.

If the power cable is carrying a voltage, V_i, the current induced in each signal wire by the capacitances is given by

$$I_i = C_s V_i (2 \pi f), \text{ where f is frequency of } V_i.$$

The induced current, I_i, will produce a voltage drop across R_s, and thus a voltage in the upper signal wire given by

$$E_c = I_i R_s = R_s C_s V_i (2 \pi f)$$

In the lower signal wire, current, I_i, induces no voltages, since there is a low resistance path to ground. The amplifier will see at its input terminals the sum of two voltages, E_s and E_c, with the magnitude of interfering voltage, E_c, determined by the circuit parameters, C_s, R_s, V_i and f.

To minimize capacitively-coupled interference, shielded wire is used, and usually the transducer is shielded. Lines of electric flux emanating from the power cable terminate on the signal cable shield. This is equivalent to having the capacitors, C_s, (B-7) connected to the shield, rather than to the signal conductors. The induced current, I_i, is now conducted through

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the shield to ground without affecting the signal conductors. (Figure B-7).
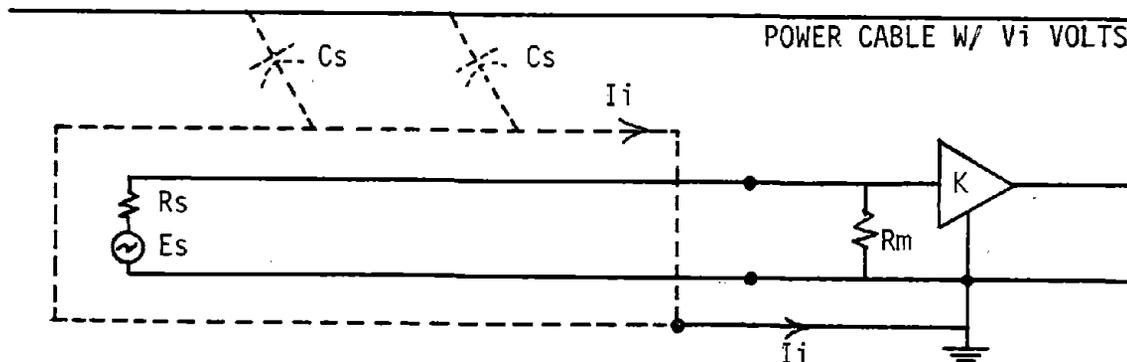
FIGURE B-7—AMPLIFIER WITH SHIELDED CABLE AND SHIELDED SOURCE

Magnetically coupled interference is caused by power cable current. Figure B-8 shows a conductor carrying current, I_i, running parallel to a signal cable. The magnetic lines of flux encircling the cables are represented by the circles.
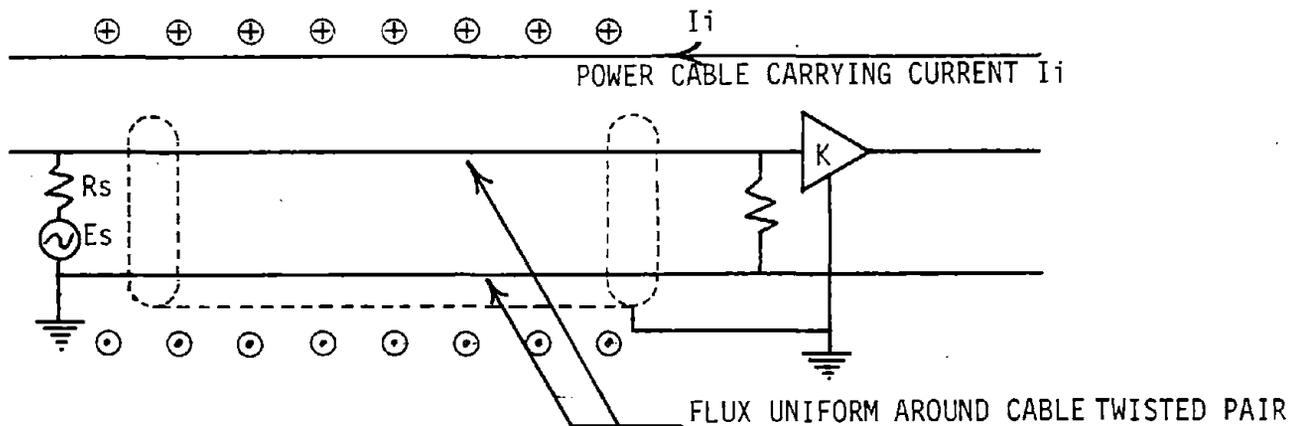
FIGURE B-8—MICROSEISMIC CABLE MAGNETICALLY LINKED TO POWER CABLE

Mutual inductance is created between the power cable and the signal wire. This is equivalent to two transformers driven by a current source, I_i, in figure B-9. The

signal wire resistance and self inductance, represented by Z_c, are a part of the interference coupling mechanism.
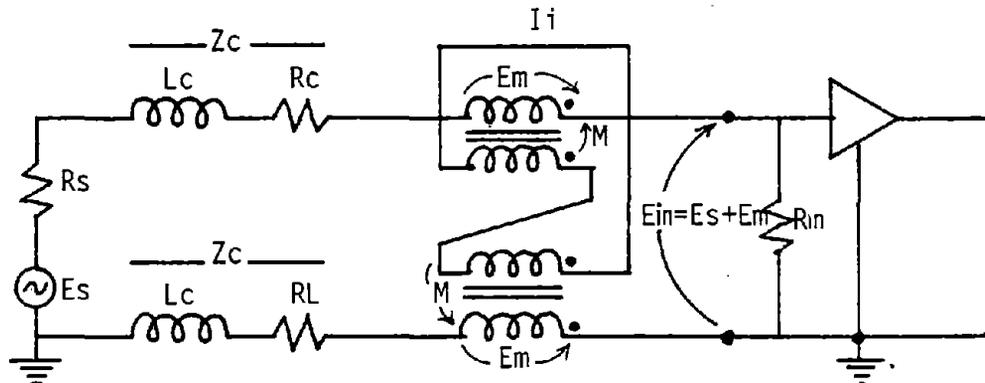
FIGURE B-9—EQUIVALENT CIRCUIT FOR MICROSEISMIC CABLE MAGNETICALLY LINKED TO A POWER CABLE

Again the assumption is made that the signal pair wire spacing is small compared to the separation of the signal cable and the power cable. Then the voltage induced in each signal wire is given by

$$E_m = I_i \, M \, (2\pi f).$$

Induced voltage, E_m, on the lower signal wire (dropped across impedance, Z_c) is prevented from entering the amplifier input by the grounds on the lower signal wire. The upper signal wire voltage, E_m, causes very little current to flow because the cable is terminated by the high input resistance R_{in}. Only a small part of voltage E_m is dropped across Z_c. R_s, being much smaller than R_{in}, drops very little E_m. Most of E_m appears at the amplifier input terminal and is added to signal E_s.

Redundant grounds (ground loops) is the third kind of interfering mechanism. Current from the power system is coupled into the instrumentation by redundant grounds.

The ground resistance, R_G, in figure B-10, carries ground current, I_G, which is assumed to originate from a source outside of the instrumentation system.
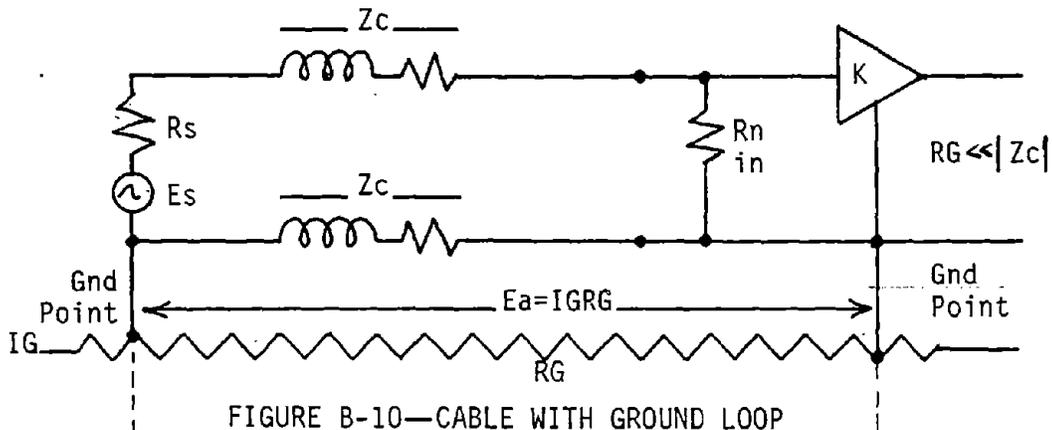
FIGURE B-10—CABLE WITH GROUND LOOP

R_G will be much smaller than impedance Z_C. Thus ground voltage E_G will appear across impedance Z_C in the lower signal lead. The impedance of the lower signal wire is approximated by resistance R_G. Figure B-11 shows a simplified equivalent circuit.
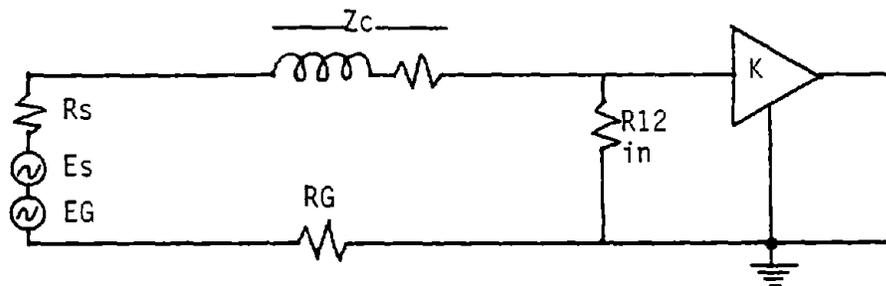
FIGURE B-11—SIMPLIFIED GROUND LOOP EQUIVALENT CIRCUIT

The interfering and signal voltages appear once again together at the amplifier input.

There are many ways by which the power system can cause ground currents, all of them involving redundant grounds, whether intentional or unintentional. Figure B-12 shows a typical situation which will cause ground currents.

When the star center point of a 120/208 transformer secondary is grounded (as a safety provision) a ground current is

generated whenever a load is also grounded (figure B-12). Load current, I_L, has two return paths to the transformer star point. The ratio of RG to Z_C determines the ground current.
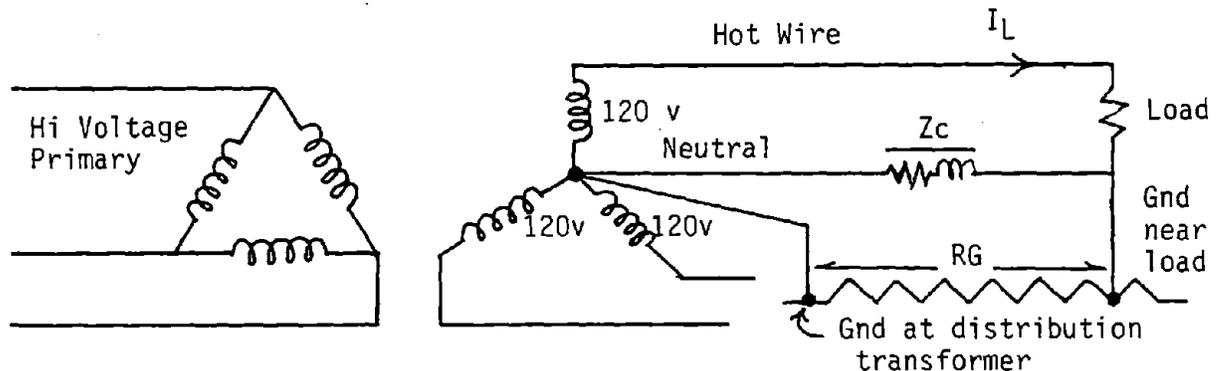
FIGURE B-12—POWER DISTRIBUTION CIRCUIT RESULTING IN GROUND CURRENT

Typically RG will approximate impedance Z_C. Therefore, half of the load current will return through ground rather than through the neutral wire. The resulting ground voltage can be several volts.

The former discussion has been restricted to three terminal amplifiers. A three terminal amplifier, often referred to as "unbalanced" or "single ended", shares a common input - output conductor.

A differential amplifier has two input terminals. The amplifier responds to the difference in voltages impressed on its input terminals. In figure B-13 the difference voltage, E_d, is defined as $E_1 - E_2$. Voltages E_1 and E_2 are referenced to ground, while E_d is not. The amplifier output voltage, E_o is given by $E_d K$. Amplifier input resistances R_{i1} and R_{i2}, and are assumed equal. The amplifier input resistance is assumed to be greater than R_S or Z_C.
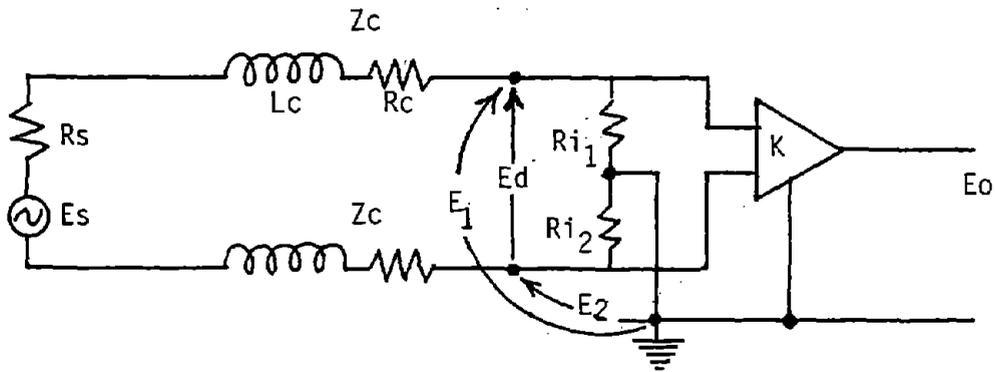
FIGURE B-13—DIFFERENTIAL AMPLIFIER WITH CABLE AND TRANSDUCER

The average of the two ground referenced input voltages, E_1 and E_2, is given by $(E_1 + E_2)/2$. This quantity is known as the common-mode voltage. Ideally the differential amplifier is absolutely unresponsive to the common-mode voltage. But in reality, the common-mode voltage does produce some output. Common-mode voltage rejection is a specified parameter for differential amplifiers. This is expressed as the ratio of the amplifier common-mode signal gain to the amplifier-differential signal gain.

The advantage of the differential amplifier becomes evident when one examines effects of interference sources. The equivalent circuit for the cable with capacitively coupled interference is shown in figure B-14.
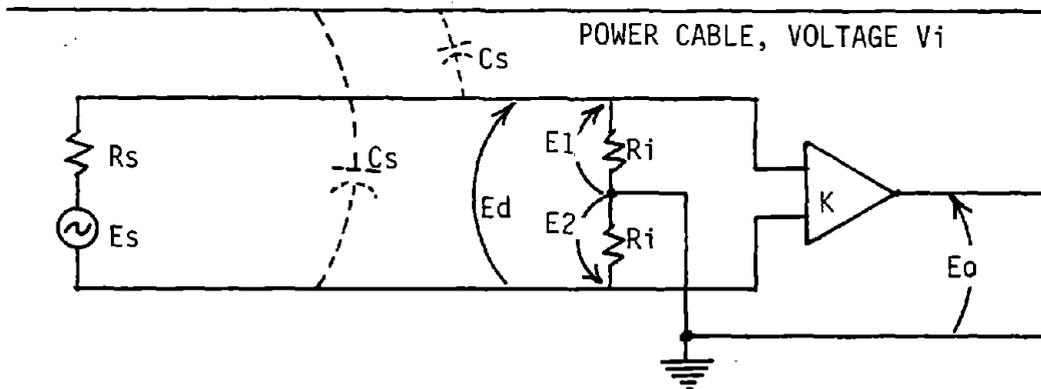
FIGURE B-14—DIFFERENTIAL AMPLIFIER WITH CAPACITIVELY COUPLED INTERFERENCE

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A current is coupled by stray capacitance, C_S to both
the upper and lower signal wires. The stray capacitances
coupling signal wire to the power wire are equal. Therefore,
interfering currents coupled to the two signal wires are equal.
These equal currents flowing into the equal amplifier-input
resistances will produce equal, cancelling input voltages,
E_1 and E_2. Only the transducer signal voltage, E_S, appears
at the amplifier input as a differential voltage.

Magnetically coupled interference is shown in figure B-15
for a differential amplifier. Cable impedance, Z_C, is assumed
small compared to amplifier input resistance, R_i. Interfer-
ence voltage, E_m, is the same in both upper and lower signal
conductors. They have the same polarity. Thus no differen-
tial voltage is produced at the amplifier input. This cancel-
lation would occur even if one signal terminal were grounded
at the transducer. Interference caused by ground loops are
minimized by a differential amplifier.
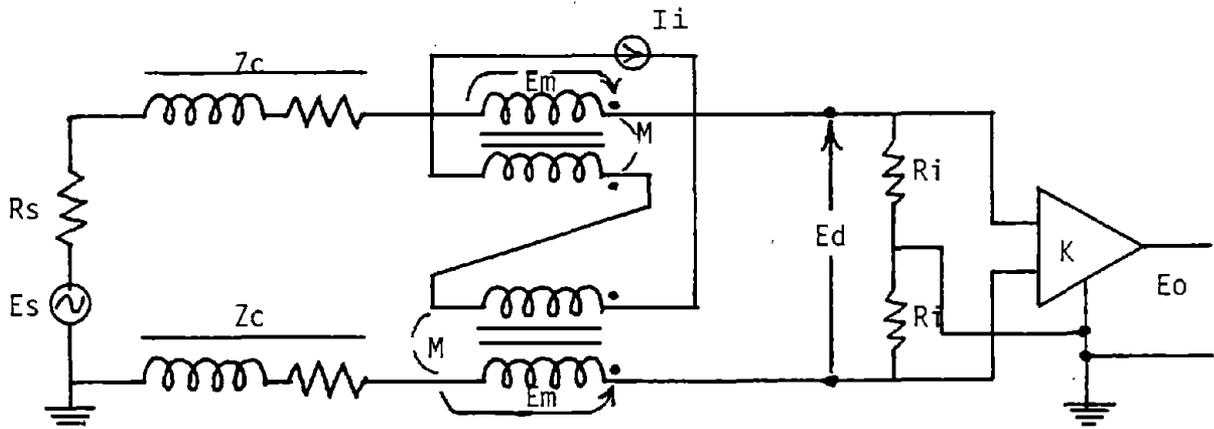
FIGURE B-15—DIFFERENTIAL AMPLIFIER WITH CABLE MAGNETICALLY LINKED TO POWER CABLE

By inspection (figure B-16), it can be seen that ground
voltage, E_G, is coupled by the lower signal wire directly into
the lower amplifier input terminal. At the upper amplifier
input terminal E_G is slightly attenuated by R_S. The amount of
the attenuation is determined by the ratio of R_S to R_i. Any
attenuation of E_G at the upper input terminal will produce a
differential voltage. The uncancelled portion of E_G will be
amplified. In the worst case, with a very large source resis-
tance, the susceptibility of the differential amplifier to
ground voltage approaches that of the single-ended amplifier.
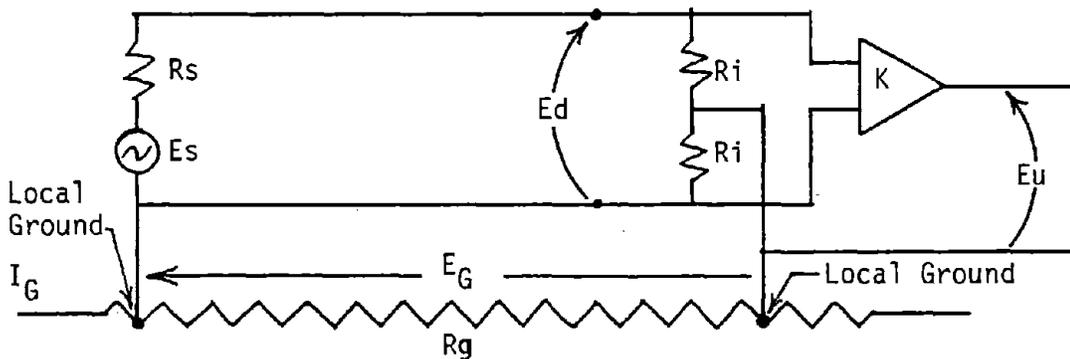
FIGURE B-16—DIFFERENTIAL AMPLIFIER WITH GROUND VOLTAGE

It has been demonstrated that an unbalanced source, with one side grounded, can lead to interference. This is true if a differential amplifier is used, although the amount of interference entering the amplifier will be less.

One way to assure that the source will be balanced is to have it floating, that is with no source terminal grounded. This makes the currents in the source signal terminals equal. Floating is acheived with velocity gages and accelerometers by electrically insulating them from ground.

Cable interference between the amplifier and the data processor can be treated in a similar manner. A differential amplifier can be easily installed at the data processor end of the cable.

It is to the users advantage to have the transducer amplifier output act as a differential source to the cable. However, differential amplifiers have an unbalanced output, with one terminal common with the power supply low side.

One can balance the differential amplifier output by floating the amplifier. The same technique is used to balance the transducer. The amplifier can be floated by providing it with its own power supply and removing the local DC power supply ground. (Figure B-16). However, besides the safety problem, a truly balanced condition has not been achieved.

Furthermore, with the floating power supply method, about half of the amplifier output voltage will appear between the amplifier output low terminal and ground. Any stray capacitance on the input leads of the amplifier to ground will tend

to hold the input circuit at ground potential. The result is
that some of the amplifier output voltage will appear as a
common-mode signal at the amplifier input. And some of this
common-mode signal will end up as a differential signal. The
amount depends on the common-mode rejection of the amplifier.

Therefore, with the circuit of figure B-17, a feedback
path has been established around the amplifier. The amount
of feedback will increase with frequency since it is primarily
caused by stray capacitance. Furthermore, the common-mode
rejection of the amplifier decreases with increasing frequency.
This increases the feedback loop gain. Change in feedback
causes gain anomalies at low frequency and instability at
higher frequences.
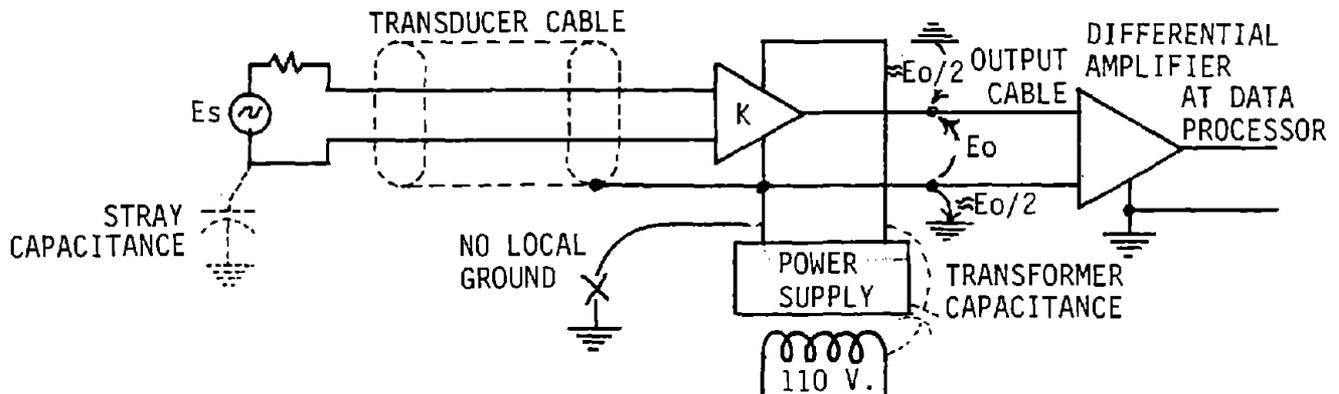
FIGURE B-17—DIFFERENTIAL AMPLIFIER WITH UNBALANCED OUTPUT

A better solution is the use of an amplifier with a differ-
ential input and output. (Figure B-18).
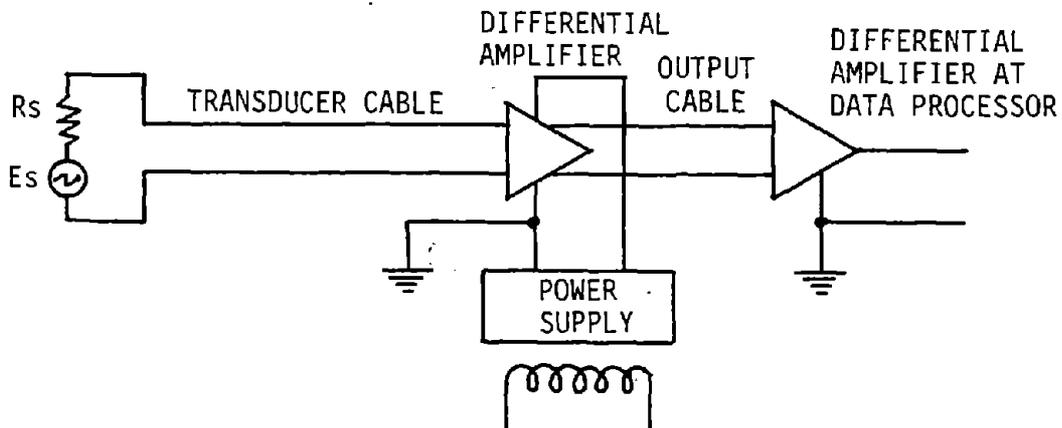
FIGURE B-18 —AMPLIFIER WITH DIFFERENTIAL INPUT AND OUTPUT

The differential input/output amplifier permits use of a grounded power supply which can power multiple amplifiers. The differential amplifier may be either full-floating or differentially balanced, with identical impedances from each output terminal to ground.

With this method the output cables are terminated at both ends into fully differential devices. Upper and lower conductors carry identical currents flowing in opposite directions. The voltages, with respect to ground, on the two conductors are equal and opposite in polarity. As a result, at any appreciable distance, the electrical and magnetic fields around the conductors very nearly cancel. Because of this flux cancellation little coupling occurs between amplifier cables. This is true even if the individual pairs are not electrically shielded.

Not having to shield individual pairs is an advantage. In most microseismic installations, groups of amplifier output cables are collected at a central point and connected to multipair cables for transmission to the data processor. Most commercially available cables with individually shielded pairs are not intended for severe environments. However, if only an overall shield is required, high quality cable is readily available. The use of an overall shield, preferably of copper, is recommended, for both single and multipair cables.

Microseismic systems have many individual lengths of both single and multipair amplifier cables. Each has its own shield. The shields cannot be permitted to float; if they are, little electrostatic shielding is provided. The shields must be grounded, but without causing ground loops. Shield currents can couple into the signal leads because of slight imbalances in the differential system. Therefore, multiple grounding of electrical shields must be avoided. A single shield ground connection should be made at the data processor as shown in figure B-19.

TRANSDUCERS   TRANSDUCER AMPLIFIER   AMPLIFIERS AT DATA PROCESSOR   SINGLE SHIELD GROUND
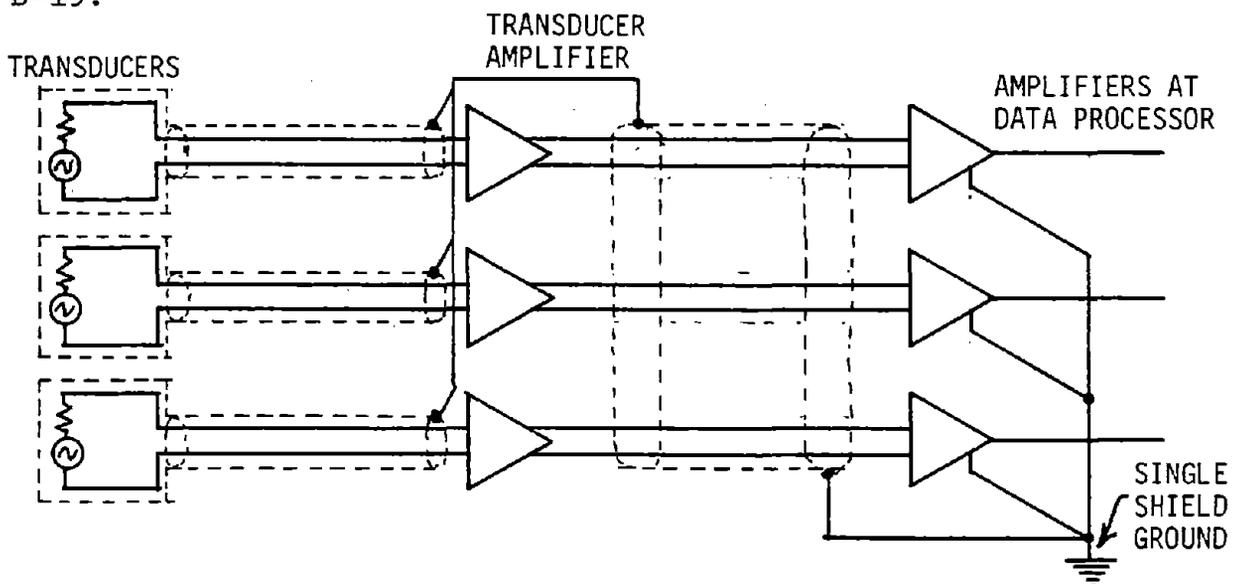
FIGURE B-19 — SHIELD CONNECTIONS FOR A MICROSEISMIC SYSTEM

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Care should be taken to connect the shields in a daisy chain fashion. Redundant shield connections, such as a wire between two transducer shields, should not be made.

Suggestions for Lowering System Noise

1)   Transducers should be electrically floated and encased in electrically shielded enclosures. Magnetic shielding of velocity gages may be necessary.

2)   Transducer cables, particularly when used with accelerometers, should be as short as possible.

3)   A differential transducer preamplifier should be used with long cables or in an electrically noisy installation.

4)   The receiving amplifier at the data processor, or the transducer amplifier (preferably both) output should be differential.

5)   All cable should have an overall metallic shield to minimize electrical field interference.

6)   Multipair cable need not have individually shielded pairs if all preamplifiers have differential outputs and receiving amplifiers have differential inputs.

7)   All shields in the system should be daisy-chained together and grounded only at the data processor end of the cable.

Microseismic System Wiring

1)   Non-magnetic metals, such as aluminum foil, provides very little shielding from magnetic interference to cables and devices at power line frequencies.

2)   Vinyl-covered cables are not generally satisfactory for underground installations. Polypropylene-covered cables designed for direct burial are preferred.

3)   Nonwicking cable should be used in wet areas.

4)   Junction boxes should be used at points where individual amplifier cables join multi-pair cables. Additional junction boxes should be provided along both single and multi-pair cables to aid in system cable fault location.

5)   Junction boxes should be drip-proof and readily accessible for service work.

6)   Junction boxes should not be electrically connected to cable shields.

7) All electrical connections should be made in junction boxes, using spade-lug connectors and high-quality plastic terminal strips with screw-down connections. Bakelite terminal strips are not satisfactory. Telephone type connection blocks with insulation displacement terminals are not satisfactory.

8) Microseismic cables should be physically separated from power cables and power apparatus, for both safety and electrical interference reduction.

9) Any electronics connected to underground cables should be able to withstand an overvoltage of at least 25 volts applied to signal input or output, either as a common-mode voltage or as a differential voltage. Additional protection will be necessary if any part of the cabling is subject to lightning.

APPENDIX C. - MANUFACTURERS OF MICROSEISMIC EQUIPMENT

A list of known manufacturers of microseismic and acoustic emission components and monitoring systems is presented in the following table.

Table C-1. List of Manufacturers

Manufacturer and Address	Components	Nonlocating Systems	Locating Systems
Acoustic Emission Technology Corp. 1812 J. Tribute Road Sacramento, CA 95815 (916) 927-3861	X	X	X
Bruel and Kjaer Instruments, Inc. 185 Forest Street Marlborough, MA. 01752 (617) 481-7000	X		X
Columbia Research Labs, Inc. MacDade Blvd. and Bullens Lane Woodlyn, PA 19094 (215) 532-9464	X		
Dunegan/Endevco Rancho Viejo Road San Juan Capistrano, CA 92675 (714) 831-9131	X	X	X
Electro-Lab Building 10 Spokane Industrial Park Spokane, WA 99126 (509) 928-0929	X		X
Geospace Corporation 5803 Glenmont Drive Houston, TX 77036 (713) 666-1611	X		
Ithaco Inc. 735 W. Clinton St. Ithaca, NY 14850 (607) 272-7640	X	X	X

Table C-1. List of Manufacturers

Manufacturer and Address	Components	Nonlocating Systems	Locating Systems
Integrated Sciences, Inc. 1134 Francis Street Longmont, CO 80501 (303) 772-6222		X	
Physical Acoustics Corp. 743 Alexander Road Princeton, NJ 08540 (609) 452-2510	X	X	X
Slope Indicator Co. 3668 Albion Place N. Seattle, WA 98103 (206) 633-3073		X	
Teledyne Geotech 3401 Shiloh Road Garland, TX 75041 (214) 271-2561	X	X	
Trans Era Corp. 3707 North Canyon Road Provo, UT 84601 (801) 224-6550			X
Walter Nold Co. 24 Birch Road Natick, MA 01760 (617) 653-1635		X	

APPENDIX D. - INTERPRETATION OF SEISMOGRAPH RECORDS

When an earthquake, rock burst, or explosion occurs, the original waves are a complex mixture of amplitudes and wavelength. A Fourier analysis shows a large number of sine waves of different wavelengths and amplitudes. The high frequencies or short wavelengths are damped out over a very short distance, so after a few miles the only components that are recorded have a period of the order of magnitude of tenths of second.

To determine the epicenter of an earthquake, the traveltimes of different components are measured. For local quakes, only the P (longitudinal) and S (transverse) waves can be measured, but since the P wave travels at a much higher velocity, the difference between the arrival times, S - P, is commonly used to compute the distance to the epicenter. Since the arrival times are dependent upon wave velocities in an area, empirical formulas can be determined for a particular geologic area. Practice has established the following empirical relationships for California earthquakes:

Distance from the epicenter = 8.5 x (S - P) kilometers, or

distance from the epicenter = 5.28 x (S - P) miles.

Traveltime of P wave = 1.37 x (S - P) seconds

for distances up to 100 km. These formulas give excellent results for major rock bursts in the Coeur d'Alene area recorded at the Newport Seismological Observatory (81 miles). Studies in the district have indicated that velocities may range from 3,000 to 23,000 fps within a mine, and with this variation, present published curves and empirical formulas are not applicable. Some work has been done to determine local traveltime curves, and it is hoped that more will be determined in the future.

It is beyond the scope of this report to discuss the details of earthquake mechanism and the interpretation of seismograms other than to explain the distinguishing elements of various events. Richter's "Elementary Seismology" or Neumann's "Principles Underlying the Interpretation of Seismograms" are recommended as excellent references.

After some experience in reading the seismograms, the ground control engineer can quickly separate the various events. These include underground blasting, bursts of varying intensity, earthquakes, surface blasts, and others. Following are examples and discussion.

The seismograph drum speed can be varied to record at 30 mm per minute laterally, or a faster 60 mm per minute. The slower speed is used for the weekend (when the mines are idle),

so that a continuous 48-hour record is obtained without a paper change. During the mine operating period, the 60 mm per minute lateral speed is used to lengthen the wave trace and permit more accuracy in reading the seismogram. The record is changed every 24 hours.

Examples of various seismic events are shown in the seismogram of figure D-1. The first event is a small rock burst from a nearby mine some 9 miles away (S - P less than 2 sec). The second is a large bench blast at an open pit mine some 185 miles away (S - P of 35 sec). The next is a small local earthquake occurring some 79 miles away (S - P of 15 sec). The last is a small distant earthquake (the S wave is damped out and not recorded).
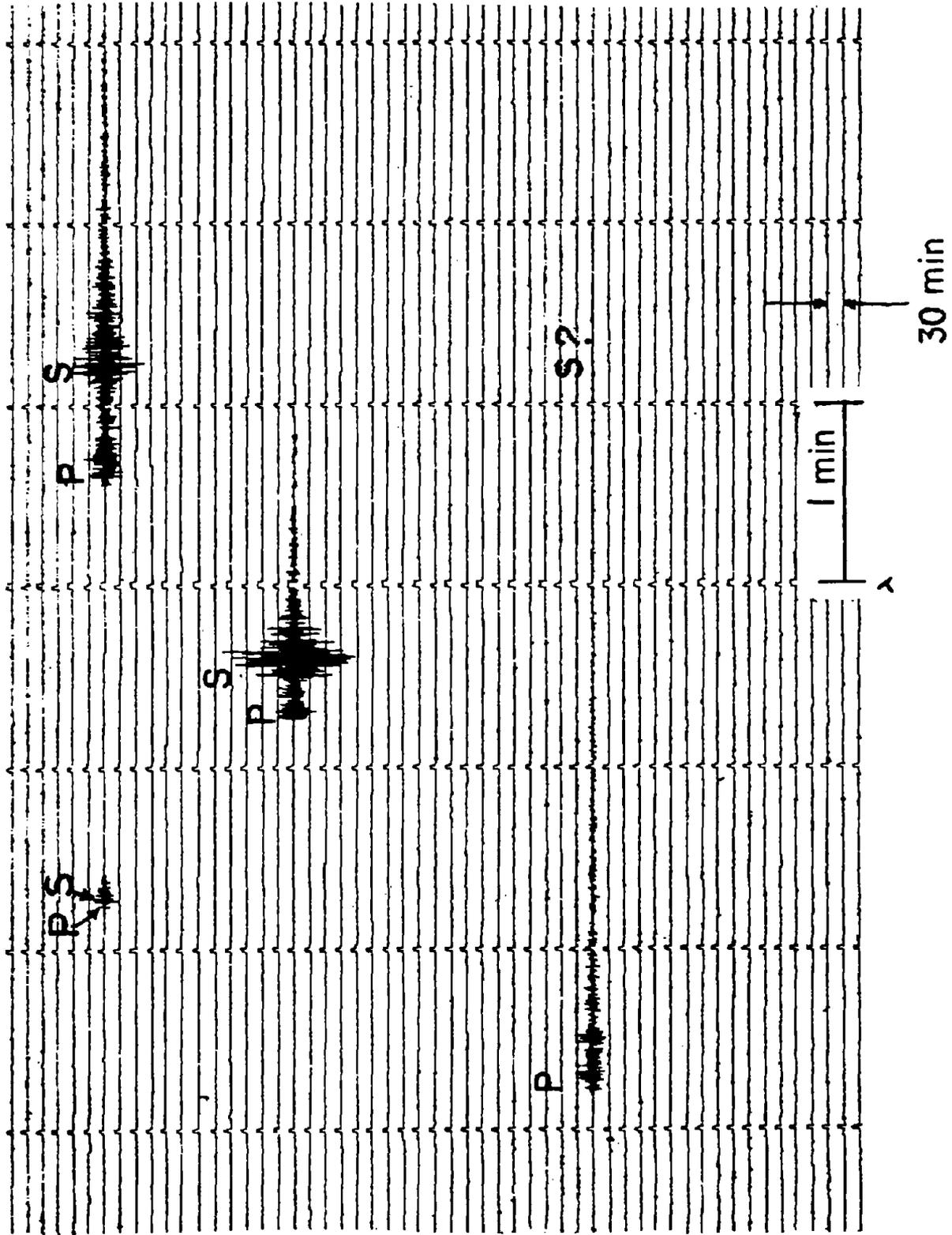
FIGURE D-1—SEISMOGRAM OF VARIOUS SEISMIC EVENTS

APPENDIX E. - MINES USING SOURCE LOCATION MONITORING SYSTEMS AND MICROSEISMIC RESEARCH ORGANIZATIONS IN U. S.

Microseismic monitoring systems have been installed throughout the world in both hard rock and coal mines. Rock burst monitoring systems are currently operating in the U. S., Canada, South Africa, Australia and Chile. Coal bump monitoring systems are currently operating in Germany, Poland, Czechoslovkia, Russia and Japan. A list of north American mines with rock burst monitoring systems is given in the following table.

Table E-1.   Mines with Monitoring Systems

Mine and address	System Type
Creighton Mine INCO Ltd. Copper Cliff, Ontario Canada POM 1NO (705) 682-4411	Electro-Lab 250 MP
Crescent Mine Bunker Hill Co. P. O. Box 29 Kellogg, ID 83837 (208) 784-1261	Electro-Lab 250 MP
Falconbridge Mine Falconbridge Nickel Mines, Ltd. Falconbridge, Ontario Canada, POM 1S0 (705) 693-2761	Electro-Lab 250 MP
Galena Mine ASARCO Inc. P. O. Box 440 Wallace, ID 83873 (208) 752-1117	Data General W/Electro-Lab Interface

Table E-1. Mines with Monitoring Systems

Mine and address	System Type
Lucky Friday Mine Hecla Mining Company P. O. Box 320 Wallace, ID 83873 (208) 752-1251	Electro-Lab 250 MP W/interactive DEC minicomputer
Star Mine Hecla Mining Company P. O. Box 320 Wallace, ID 83873 (208) 752-1251	IBM Sys. 7 W/Electro-Lab interface
Sunshine Mine P. O. Box 1080 Kellogg, ID 83837 (208) 783-1211	Electro-Lab 250 MP W/interactive IBM minicomputer

Microseismic Research Organizations in U. S.

A list of government and university research organizations involved in microseismic monitoring is presented.

Denver Research Center
U. S. Bureau of Mines
Bldg. 20, Denver Federal Center
Denver, CO 80225
(303) 234-3018
Attn: Mr. Fred Leighton

Spokane Research Center
U. S. Bureau of Mines
E. 315 Montgomery Ave.
Spokane, WA 99207
(509) 484-1610
Attn: Mr. Roger McVey

Rock Mechanics Laboratory
Department of Mineral Engineering
The Pennsylvania State University
University Park, PA 16802
(814) 863-1620
Attn: Dr. H. Reginald Hardy, Jr.

Civil Engineering Department
Drexel University
23rd and Chestnut Streets
Philadelphia, PA 19104
(215) 895-2364
Attn: Dr. Robert Koerner

APPENDIX F. ENERGY CALCULATIONS

By considering the energy radiating outward from a spherical source, the seismic energy of a rock noise event can be approximated from an oscillogram of that rock noise event. The calculations can be made for either particle velocity or particle acceleration, that is, with velocity gage geophones or accelerometer geophones.

Velocity Gage Geophone

For a spherical source of small radius and with only normal stress $\sigma\pi$ acting, the outward flow of energy across a spherical surface at some radius r (that is, what the gage would respond to) is

$$E = 4\pi r^2 \int_{\tau_i}^{\tau_2} \sigma_{rr} \frac{\partial u}{\partial t} \, dt \qquad (F-1)$$

where the integration is taken over the time interval τ_i to τ_2 and $\frac{\partial u}{\partial t}$ is the rate of change of displacement of the spherical surface at r owing to σ_{rr}. Using the relationship $\sigma_{rr} = pc \frac{\partial u}{\partial t}$, equation F-1 can be simplified to

$$E = 4\pi \, p \, cr^2 \int_{\tau_i}^{\tau_2} \left(\frac{\partial u}{\partial t}\right)^2 \, dt \qquad (F-2)$$

where p and c are the medium density and seismic velocity respectively. Since $\frac{\partial u}{\partial t}^2$ is $\hat{v}^2$ where $\hat{v}$ is the average particle velocity, and

$$\int_{\tau_i}^{\tau_2} dt = T$$

the duration of the stress pulse,

$$E = 4\pi \, p \, cr^2 \, \hat{v}^2 T \qquad (F-3)$$

and is the total energy radiated outward. Since the total energy consists of both kinetic and potential energy, assumed equal, the seismic strain energy radiated outward become

$$E = 2\pi \, p \, cr^2 \hat{v}^2 T. \qquad (F-4)$$

Accelerometer Gage Geophone

Since the seismic wave propagates in a sinusiodal manner, the average particle acceleration, $\hat{a}$, can be obtained from the average particle velocity, $\hat{v}$, from the relationship

$$\hat{v}^2 = \frac{\hat{a}^2}{\omega^2}$$

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where ω^2 is the angular frequency and $\omega = 2\pi f$. Making these substitutions into equation F-4, the seismic strain energy-particle acceleration relationship becomes

$$E = \frac{pcr^2\hat{a}^2T}{2\pi f^2} \qquad (F-5)$$

Energy Calculation Procedures

Energy calculations from field data are fairly straight-forward for velocity gage data but are a little more involved for acceleration gage data, because the frequency of the rock noise waveform enters into the calculations. The standard field procedure has been to determine the energy for the whole wave by combining the P- and S-wave portions and by using a combined average seismic velocity. The average particle velocity $\hat{v}$, or the average particle acceleration, $\hat{a}$, of the seismic record is measured, and for acceleration records the average frequency of the seismic wave in Hz is determined from the record. Hence, knowing the mass density of the rock, equations F-4 and F-5 can be evaluated provided the distance from geophone to source, r, is known. This can be determined from source locations or from S-P-wave arrival time differences using equation G-4.

With an array of geophones one can also determine the energy of the seismic event at the source by plotting log E versus r for all the geophones detecting the event, determining the best-fit energy-distance relationship, that is, energy propagation law, and then extrapolating this relationship back to the source.

Once the energy released at the source has been determined, the volume of rock broken or destressed at the source can be determined from the relationship

$$W_S = \frac{3}{8}\frac{p^2}{G}V_{ac},$$

where W_S is the seismic energy released at the source,
   p is the applied stress field at the source,
   G is the modulus of rigidity of the rock, and
   V_{ac} is the volume of rock affected.
Thus, assuming a stress field of 10,000 psi, and a modulus of rigidity of 4×10^6 psi, an energy release of 10^{-5} ft/lb results in 7.40×10^{-9} cu ft of broken rock (the formation of a micro-crack), while an energy release of 10^6 ft/lb (rock burst) results in the breaking up of 7.40×10^2 cu ft of rock. Using this type of data one can make quantitative estimates of what is happening to the rock structure as rock noises, bumps, small bursts, and rock bursts occur.

It should be mentioned that with automatic monitoring equipment, RBM or minicomputer RBM, these calculations can be performed in real time by integrating and summing circuits. In addition, there are other more sophisticated mathematical procedures for determining energy from seismic wave form data.

Where the monitoring system has been well calibrated, that is, the sensitivity of gages is known or measured, the amplification is known and correct, and the real time speed of the oscillographic records is accurately known, comparisons of the seismic energy released by explosives and calculated by these methods have shown good agreement--well within an order of magnitude.

APPENDIX G. - SOURCE LOCATION TECHNIQUES

The basic problem in rock noise source location methods is to obtain the three coordinates required to fix the source point in three-dimensional space.

Direct Solution Source Locations

The most direct approach to this problem is through the use of the standard distance equation

$$d_i = \sqrt{(x-a_i)^2 + (y-b_i)^2 + (z-c_i)^2}, \qquad \text{(G-1)}$$

in which

a_i, b_i, c_i are the ith geophone coordinates, d_i is the distance from the source to the ith geophone, and x, y, z are the unknown source coordinates. To solve for these unknown coordinates x, y, and z, it is necessary to have sufficient information to reduce equations G-1 to three linearly independent equations in three unknowns.

It is also possible to describe the unknown distance from source to geophone from seismic velocity and arrival time data by the expression

$$d_i = V_i t_i, \qquad \text{(G-2)}$$

in which

V_i is the seismic wave velocity from the source to the ith geophone and t_i is the time required for the wave to travel from the source to the ith geophone.

The basic procedure is to equate the righthand sides of equations G-1 and G-2 with information from a sufficient number of geophones to develop three linear equations in three unknowns, x, y, and z.

The distance, d_i, can be described in two ways--first by use of only the P-wave arrival times, and second by use of the difference between the arrival times of the S and P waves at each geophone. Thus, there are two basic methods, the P-wave method and the S-P wave method.

The equations used in these methods are

$$d_i - V_i^P t_i^P$$
(P-wave method) $\qquad$ (G-3)

$$d_i = \Delta t_i^{S-P} / \left(\frac{1}{V_i^S} - \frac{1}{V_i^P} \right)$$

(S-P-wave method) $\qquad$ (G-4)

where:

$V_i{}^S$ and $V_i{}^P$ are the S-and-P-wave velocities in the direction from the source to each geophone; $t_i{}^P$ are the relative times of the first arrival of the P-wave at each geophone; these times are measured relative to the first arrival at the geophone closest to the source (fig. G-1); and $\Delta t_i{}^{S-P}$ are the differences in the times of arrival of the S-wave and the times of arrival of the P-wave at each geophone (fig. G-1).

A microseismic record such as shown in figure G-1 supplies sufficient information to completely describe d_i by the S-P-wave method. However, the time $t_i{}^P$ shown in figure G-1 is not at all the total time the wave took to propagate from the source to the geophone, because the time measurements begin when the geophone closest to the source receives the arrival of the seismic wave. Thus, there is an unknown time, $t_o{}^P$, which is the time for the P-wave to propagate from the source to the nearest geophone. This time corresponds to an unknown distance, $d_o = V_o{}^P t_o{}^P$, which can be geometrically described as

$$V_o{}^P t_o{}^P = \sqrt{(x-a_o)^2 + (y-b_o)^2 + (z-c_o)^2}.$$

If the seismic velocities are similar or t_o is short, then

$$V_o{}^P t_o{}^P \cong V_i{}^P t_o{}^P.$$

The total distance from the source to the ith geophone then becomes

$$V_i{}^P (t_i{}^P + t_o{}^P) = \sqrt{(x-a_i)^2 + (y-b_i)^2 + (z-c_i)^2}.$$

Thus, to obtain d_i in equation G-2, we have

$$d_i + \sqrt{(x-a_o)^2 + (y-b_o)^2 + (z-c_o)^2}$$
$$= \sqrt{(x-a_i)^2 + (y-b_i)^2 + (z-c_i)^2} \qquad (G-5)$$

where i has values of 1 to 4. In equation G-5, d_i is known because of equation G-3; therefore, all quantities are known except the values of x, y, and z.

For the S-P-wave method, d_i in equation G-1 is known because of equation G-4. Therefore,

$$d_i = \sqrt{(x-a_i)^2 + (y-b_i)^2 + (z-c_i)^2} \qquad (G-6)$$

where i takes on values of 1 to 4.
Equations G-5 and G-6 are now in a form suitable for solution.
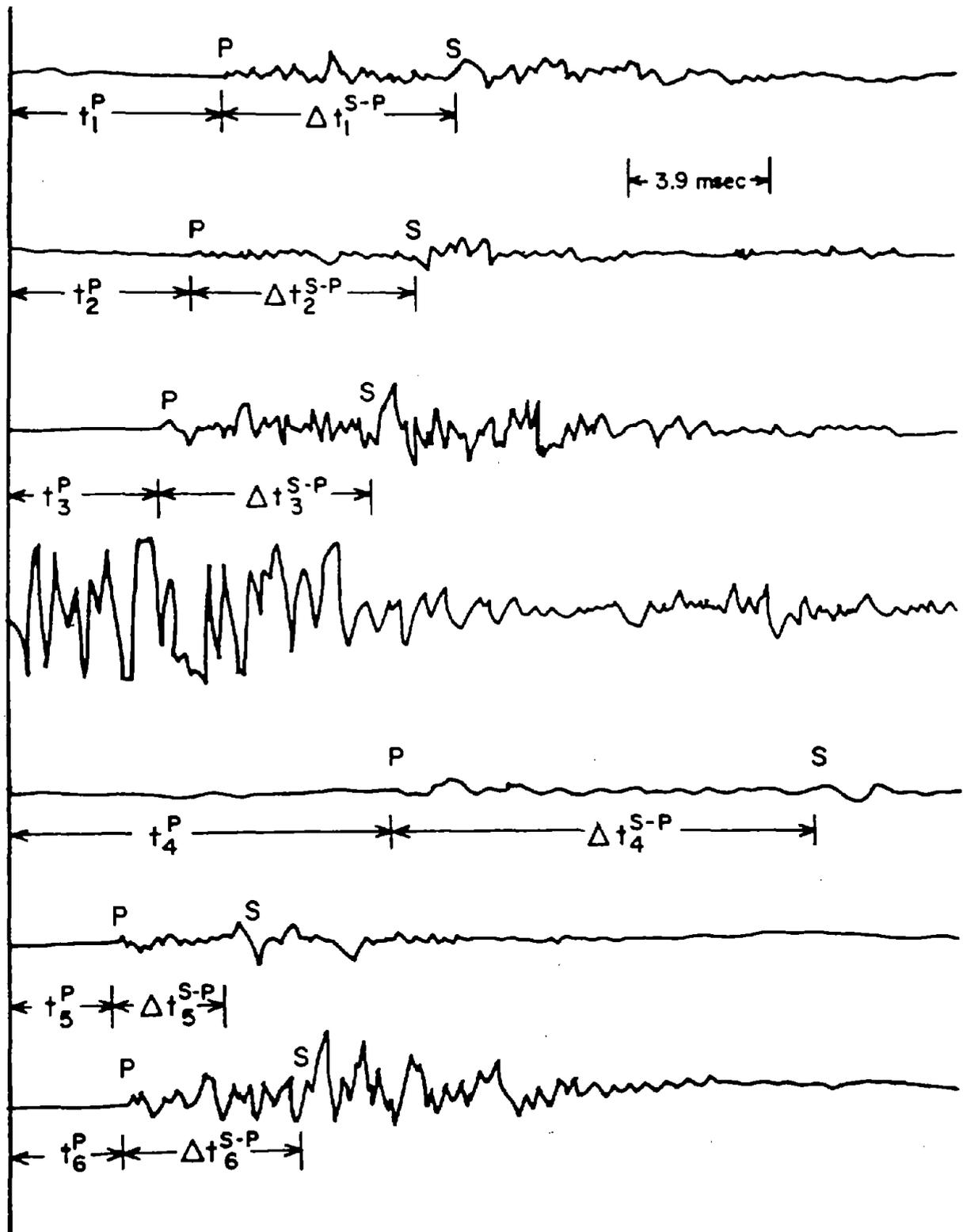
FIGURE G-1— MICROSEISMIC RECORD OF ROCK NOISE

Since the solutions for the two basic methods are similar, they are manipulated together below. Both sides of equations G-5 and G-6 are squared and simplified to give:

$$L_i - 2(\alpha_i x + \beta_i y + \gamma_i z)$$
$$= -2d_i \sqrt{(x-a_o)^2 + (y-b_o)^2 + (z-c_o)^2} \quad (P) \tag{G-7}$$

$$K_i + 2(a_i x + b_i y + c_i z) = x^2 + y^2 + z^2 \quad (S-P) \tag{G-8}$$

where

$$
\left.
\begin{aligned}
& L_i = d_i{}^2 + a_o{}^2 + b_o{}^2 + c_o{}^2 \\
& \quad -a_i{}^2 -b_i{}^2 -c_i{}^2, \\
& \alpha_i = a_o - a_i, \\
& \beta_i = b_o - b_i, \\
& \gamma_i = c_o - c_i, \text{ and} \\
& K_i = d_i{}^2 - a_i{}^2 - b_i{}^2 - c_i{}^2.
\end{aligned}
\right\} \quad (S-P)
$$

Each of the P-wave method constants are made up of information from two geophones, the coordinates of the geophone closest to the source and the coordinates of the ith geophone. The S-P-wave method constants contain only the ith geophone coordinates. The result of this difference in the makeup of the constants is that the P-wave method requires information from one more geophone than the S-P-wave method. Thus, the P-wave method requires information from five geophones and the S-P-wave method requires information from four geophones in order to obtain three linear independent equations.

If one now subtracts i = 2,3, and 4 from i = 1 for both methods, the result is three equations in three unknowns and the radical term is thus eliminated in the P-wave method and the squared coordinate terms are eliminated in the S-P wave method. After subtraction, i has the values 2, 3, and 4 and one obtains

$$\frac{L_1}{d_1} - \frac{L_i}{d_i} = \frac{2}{d_1}(\alpha_1 x + \beta_1 y + \gamma_1 z) - \frac{2}{d_i}(\alpha_i x + \beta_i y + \gamma_i z) \quad (P) \tag{G-9}$$

and $K_i - K_1 = 2x(a_1-a_i) + 2y(b_1-b_i) + 2z(c_1-c_i) \quad (S-P).$
$$\tag{G-10}$$

One now makes substitutions as follows:

P	S-P
$\left(\dfrac{L_1}{d_1} - \dfrac{L_i}{d_i}\right) = H_{1i}$	$K_i - K_1 = H_{1i}$
	$2(a_1 - a_i) = A_{1i}$
$2\left(\dfrac{\alpha_1}{d_1} - \dfrac{\alpha_i}{d_i}\right) = A_{1i}$	$2(b_1 - b_i) = B_{1i}$
	$2(c_1 - c_i) = C_{1i}$
$2\left(\dfrac{\beta_1}{d_1} - \dfrac{\beta_i}{d_i}\right) = B_{1i}$	
$2\left(\dfrac{\gamma_1}{d_1} \quad \dfrac{\gamma_i}{d_i}\right) = C_{1i}$	

Three equations in three unknowns (equations G-9 and G-10) result
as follows:

$$
\left.
\begin{array}{l}
H_{12} = A_{12}x + B_{12}y + C_{12}z \\[6pt]
H_{13} = A_{13}x + B_{13}y + C_{13}z \\[6pt]
H_{14} = A_{14}x + B_{14}y + C_{14}z
\end{array}
\right\} \qquad \text{(G-11)}
$$

If the geophones are in a planar array, the solution is not
unique, because mirror image solutions exist, one on either side
of the plane.

Least Squares Direct Solutions

The least squares method requires seismic information from at least one geophone more than the minimum number required for direct solution methods, and, in general, the more information used the better the solution. Equations G-11 rewritten as the normal equations of planes are

$$l_i x + m_i y + n_i z = p_i \qquad\qquad (G-12)$$

where $i = 1,2,3 \ldots n$ and

$$l_i = A_i / \sqrt{A_i^2 + B_i^2 + C_i^2},$$

$$m_i = B_i / \sqrt{A_i^2 + B_i^2 + C_i^2},$$

$$n_i = C_i / \sqrt{A_i^2 + B_i^2 + C_i^2}, \quad \text{and}$$

$$p_i = H_i / \sqrt{A_i^2 + B_i^2 + C_i^2}.$$

The coefficients l_i, m_i, n_i are now the direction cosines of a line from the origin of the coordinate system perpendicular to the ith plane, and p_i is the length of this perpendicular line.

Four or more planes are being considered, and the values of l_i, m_i, n_i and p_i are determined by geophone coordinate values, directional seismic velocity values, and arrival times. Hence, errors in these coefficients generate errors in the orientation of the planes making it unlikely that four or more planes will intersect at one point. The best approximation for the point of intersection of the planes lies at some minimum perpendicular distance from each plane, as shown for two dimensions in figure G-2.

By definition, the least squares method is based on minimizing the random errors in the data. In this case, these errors are represented as the perpendicular distances to each plane from some point (x_c, y_c, z_c). These perpendicular distances, R_i, may be described as

$$R_i = l_i x_c + m_i y_c + n_i z_c - p_i. \qquad\qquad (G-13)$$

Squaring these distances, summing them, and minimizing the sum with respect to each variable determines the point x_c, y_c, z_c. The sum of the distances squared is

$$Q = \sum_{i=1}^{n} R_i^2 = \sum_{i=1}^{n} \left[l_i x_c + m_i y_c + n_i z_c - p_i \right]^2. \qquad\qquad (G-14)$$
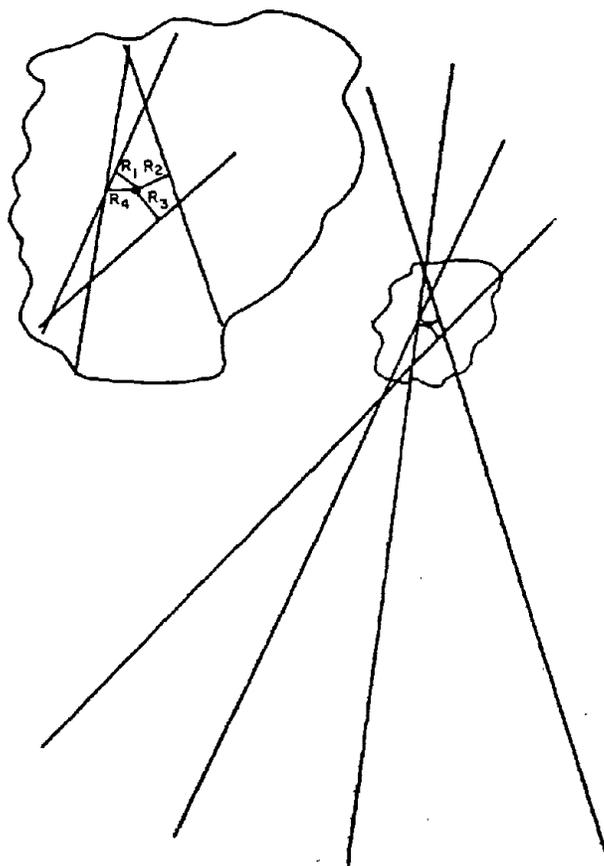
FIGURE G-2 — TWO-DIMENSIONAL REPRESENTATION OF LEAST SQUARES SOLUTION,
WHERE THE SUMS OF THE Ri's HAVE BEEN MINIMIZED

To minimize Q, differentiate equation G-14 with respect to x_c, y_c and z_c and equate each result to zero. Thus

$$\frac{\partial Q}{\partial x_c} = x_c \, \Sigma \, l_i{}^2 + y_c \, \Sigma \, l_i \, m_i + z_c \, \Sigma \, l_i n_i - \Sigma \, l_i p_i = 0,$$

$$\frac{\partial Q}{\partial y_c} = x_c \, \Sigma \, m_i l_i + y_c \, \Sigma \, m_i{}^2 + z_c \, \Sigma \, m_i n_i - \Sigma \, m_i p_i = 0, \text{ and}$$

(G-15)

$$\frac{\partial Q}{\partial z_c} = x_c \, \Sigma \, n_i l_i + y_c \, \Sigma \, n_i m_i + z_c \, \Sigma \, n_i{}^2 - \Sigma \, n_i p_i = 0,$$

where the equations are summed from i = 1 to i = n.
    Equations G-15 may be written as

$$x_c \, \Sigma \, l_i{}^2 + y_c \, \Sigma \, l_i m_i + z_c \, \Sigma \, l_i n_i = \Sigma \, l_i p_i,$$

$$x_c \, \Sigma \, m_i l_i + y_c \, \Sigma \, m_i{}^2 + z_c \, \Sigma \, m_i n_i = \Sigma \, m_i p_i \quad \text{and} \qquad \text{(G-16)}$$

$$x_c \, \Sigma \, n_i l_i + y_c \, \Sigma \, n_i m_i + z_c \, \Sigma \, n_i{}^2 = \Sigma \, n_i p_i,$$

where the summation is from i = 1 to i = n.

Solving these equations for x_c, y_c, z_c gives the point that best represents the seismic event source location. Equations G-16 may be applied to either the basic P-wave or S-P-wave method.

The standard deviation for this solution may be described by the equation

$$S_e{}^2 = \frac{\Sigma \, R_i{}^2}{n-3} = \frac{\Sigma \, [l_i x_c + m_i y_c + n_i z_c - p_i]^2}{n-3},$$

(G-17)

where S_e is the standard deviation,
    R_i is the ith perpendicular distance, and

    n is the number of equations in G-13.
Equation G-17 may be expanded and simplified to yield

$$S_e{}^2 = \frac{\Sigma \, p_i{}^2 - x_c \, \Sigma \, l_i p_i - y_c \, \Sigma \, m_i p_i - z_c \, \Sigma \, n_i p_i}{n-3}.$$

(G-18)

Least Squares Solution For a Constant Velocity Media

If constant velocity is assumed in all directions, the basic P-wave equations can be modified such that, with a minimum of six geophones, it is possible to solve for the source coordinates x_c, y_c, z_c and V, the P-wave velocity of the seismic wave in the media. This solution is derived in its least squares form as follows:

Equation G-7 is

$$L_i - 2(\alpha_i x + \beta_i y + \gamma_i z) = -2d_i \sqrt{(x-a_o)^2 + (y-b_o)^2 + (z-c_o)^2} \qquad (G-7)$$

where: $L_i = d_i^2 + a_o^2 + b_o^2 + c_o^2 - a_i^2 - b_i^2 - c_i^2$,

$\alpha_i = a_o - a_i$,

$\beta_i = b_o - b_i$,

$\gamma_i = c_o - c_i$,

$a_i b_i c_i$ are the coordinates of the ith geophone,

x, y, z are the source coordinates,

and

$a_o b_o c_o$ are the coordinates of the geophone closest to the source.

Dividing equation G-12 by d_i gives

$$d_i + \frac{M_i}{d_i} - \frac{2}{d_i}\left[\alpha_i x + \beta_i y + \gamma_i z\right] =$$

$$-2\sqrt{(x-a_o)^2 + (y-b_o)^2 + (z-c_o)^2} \quad , \qquad (G-19)$$

where

$$M_i = a_o^2 + b_o^2 + c_o^2 - a_i^2 - b_i^2 - c_i^2 \quad . \qquad (G-20)$$

Since the expression on the right hand side of equation G-19 is constant, one can subtract equation G-20 with $i = j = 2,3,4,5 \ldots m$ from equation G-19 with $i - 1$ to obtain

$$d_1 - d_j + \frac{M_1}{d_1} - \frac{M_j}{d_j} - \frac{2}{d_i}\left[\alpha_1 x + \beta_1 y + \gamma_1 z\right]$$

$$+ \frac{2}{d_j}\left[\alpha_j x + \beta_j y + \gamma_j z\right] = 0 . \qquad (G-21)$$

If t_1 is the arrival time of the P-wave at the geophone closest to the source, and t_j is the arrival time of the P-wave at the *i*th geophone, and V is the constant seismic velocity, then the distance d_j is given by

$$d_j = (t_j - t_1)V = \Delta t_j V, \qquad \text{(G-22)}$$

where Δt_j is the difference in arrival time.

Substitution of equations G-22 into equations G-21 and multiplication by V gives

$$V^2 (\Delta t_1 - \Delta t_j) + \left(\frac{M_1}{\Delta t_1} - \frac{M_j}{\Delta t_j} \right) = \frac{2}{\Delta t_1} \left[\alpha_1 x + \beta_1 y + \gamma_1 z \right]$$

$$- \frac{2}{\Delta t_j} \left[\alpha_j x + \beta_j y + \gamma_j z \right], \qquad \text{(G-23)}$$

$$\text{where } j = 2,3,4 \ldots m.$$

If

$$H_j = \frac{M_1}{\Delta t_1} - \frac{M_j}{\Delta t_j},$$

$$A_j = 2 \left[\frac{\alpha_1}{\Delta t_1} - \frac{\alpha_j}{\Delta t_j} \right],$$

$$B_j = 2 \left[\frac{\beta_1}{\Delta t_1} - \frac{\beta_j}{\Delta t_j} \right],$$

$$C_j = 2 \left[\frac{\gamma_1}{\Delta t_1} - \frac{\gamma_j}{\Delta t_j} \right], \quad \text{and} \qquad \text{(G-24)}$$

$$D_j = \Delta t_1 - \Delta t_j,$$

and equations G-24 is substituted into equations G-23 one obtains

$$H_j + D_j V^2 = A_j x + B_j y + C_j z, \qquad \text{(G-25)}$$

$$\text{where } j = 2,3,4 \ldots m.$$

If $H_j + D_j V^2 = P_j$, one again has the general equations of planes. Normalizing these equations one obtains

$$l_j x + m_j y + n_j z = p_j, \tag{G-26}$$

where

$$l_j = A_j / \sqrt{A_j{}^2 + B_j{}^2 + C_j{}^2} \quad ,$$

$$m_j = B_j / \sqrt{A_j{}^2 + B_j{}^2 + C_j{}^2} \quad ,$$

$$n_j = C_j / \sqrt{A_j{}^2 + B_j{}^2 + C_j{}^2} \quad , \text{ and}$$

$$p_j = P_j / \sqrt{A_j{}^2 + B_j{}^2 + C_j{}^2} \quad .$$

The quantities l_j, m_j, n_j are the direction consines of a line from the origin perpendicular to the ith plane and p_j is the length of that line. Again, errors in Δt measurements and geophone coordinate values may cause four or more planes to not coincide at one point. As in the previous least squares solution, one may describe the perpendicular distance R_j from each plane to a point x_c, y_c, z_c and minimize the sum of the squares of all those distances. The distance is

$$R_j = l_j x_c + m_j y_c + n_j z_c - p_j. \tag{G-27}$$

The quantity p_j is the sum of two parts

$$p_j = \frac{H_j + D_j \bar{V}^2}{\sqrt{A_j{}^2 + B_j{}^2 + C_j{}^2}} . \tag{G-28}$$

Thus,

$$h_j = \frac{H_j}{\sqrt{A_j{}^2 + B_j{}^2 + C_j{}^2}} \quad \text{and}$$

$$s_j = \frac{D_j}{\sqrt{A_j{}^2 + B_j{}^2 + C_j{}^2}} . \tag{G-29}$$

Then

$$p_j = h_j + s_j V^2 . \tag{G-30}$$

One may now write equation G-27 as

$$R_j = l_j x_c + m_j y_c + n_j z_c - h_j - s_j V^2 . \tag{G-31}$$

Thus, the perpendicular distance from x_c, y_c, z_c to each plane in normal form has now been described. Proceeding with the least squares, one sums the squares of these distances

$$Q = \sum_{j=2}^{m} R_j{}^2 = \sum_{j=2}^{m} \left[l_j x_c + m_j y_c + n_j z_c - h_j - s_j V^2 \right]^2,$$

$$(G-32)$$

and minimizes this sum with respect to each variable. Thus,

$$\frac{\partial Q}{\partial x_c} = \Sigma \, 2l_j \left[l_j x_c + m_j y_c + n_j z_c - h_j - s_j V^2 \right] = 0$$

$$\frac{\partial Q}{\partial y_c} = \Sigma \, 2m_j \left[l_j x_c + m_j y_c + n_j z_c - h_j - s_j V^2 \right] = 0, \quad (G-33)$$

$$\frac{\partial Q}{\partial z_c} = \Sigma \, 2n_j \left[l_j x_c + m_j y_c + n_j z_c - h_j - s_j V^2 \right] = 0, \text{ and}$$

$$\frac{\partial Q}{\partial V} = \Sigma^{-} 4s_j V \left[l_j x_c + m_j y_c + n_j z_c - h_j - s_j V^2 \right] = 0,$$

where the equations are summed from $j = 2$ to $j = m$.

These equations are rewritten as

$$x_c \Sigma \, l_j{}^2 + y_c \Sigma \, l_j m_j + z_c \Sigma \, l_j n_j - V^2 \Sigma \, l_j s_j = \Sigma \, l_j h_j,$$

$$x_c \Sigma \, m_j l_j + y_c \Sigma \, m_j{}^2 + z_c \Sigma \, m_j n_j - V^2 \Sigma \, m_j s_j = \Sigma \, m_j h_j, \quad (G-34)$$

$$x_c \Sigma \, n_j l_j + y_c \Sigma \, n_j m_j + z_c \Sigma \, n_j{}^2 - V^2 \Sigma \, n_j s_j = \Sigma \, n_j h_j, \text{ and}$$

$$x_c \Sigma \, s_j l_j + y_c \Sigma \, s_j m_j + z_c \Sigma \, s_j n_j - V^2 \Sigma \, s_j{}^2 = \Sigma \, s_j h_j,$$

where the summation is from $j = 2$ to $j = m$.

The solution of these equations gives the least squares values of the source x_c, y_c, z_c and the velocity squared, V^2.

The standard deviation for this solution may be described by

$$S_e^2 = \frac{\Sigma R_i^2}{n-4} = \frac{\Sigma \left[l_j x_c + m_j y_c + n_j z_j - h_j - s_j V^2 \right]^2}{n-4} ,$$

(G-35)

where S_e is the standard deviation,

R_i is the ith perpendicular distance, and

n is the number of equations in G-34.

Equation G-35 may be expanded and simplified to yield

$$S_e^2 = \frac{\Sigma h_j^2 - x_c \Sigma h_j l_j - y_c \Sigma h_j m_j - z_c \Sigma h_j n_j + V^2 \Sigma h_j s_j}{n-4} .$$

(G-36)

Least Squares Iterative Solution

The previous direct solution source location methods work well when the events detected lie within the geophone array-- usually the case for most monitoring applications. However, when the event lies outside the geophone array these direct solutions become inaccurate to very inaccurate. This is because the direct solutions are based on a linearization of a system of equations that are nonlinear. This is achieved by assuming that there is negligible P-wave velocity variation in any travel path from the time of the event until the first geophone is hit. In addition, the data for the first geophone doesn't enter into the equations. Therefore, when an event occurs outside the geophone array, the direct solution method breaks down.

To solve the nonlinear set of equations using the arrival time difference method requires a similar but somewhat different approach. Starting with equation G-1

$$d_i = \sqrt{(x - t_i)^2 + (y-b_i)^2 + (z - c_i)^2} \qquad \text{(G-1)}$$

The distance d_i can also be expressed as

$$d_i = V_i \, (t_i - t) \qquad \text{(G-37)}$$

instead of

$$d_i = V_i t_i \qquad \text{(G-2)}$$

as done previously. The t is now the time of origin of the event, or the 0 time. Substituting G-37 into G-1 gives

$$V_i \, (t_i - t) = \sqrt{(x-a_i)^2 + (y-b_i)^2 + (z-c_i)^2} \qquad \text{(G-38)}$$

Squaring both sides of this equation now results in

$$V_i^2 \, (t_i - t)^2 = (x-a_i)^2 + (y-b_i)^2 + (z-c_i)^2 \qquad \text{(G-39)}$$

a set of nonlinear equations.

If the V_i and t_i were all known exactly, then data from three geophone stations would be enough to solve equation G-39. As stated before, we don't know the time it took the signal to reach the first geophone, and the V_i and t_i are not exact measurements. Hence, equation G-39 must be solved by a trial and error or iterative approach.

If the V_i are known and assumed constant, then data from at least 5 geophone locations are necessary to solve equation G-39 for the unknown x, y, z and t. If the V_i are unknown and assumed constant, then data from at least 6 geophone locations are necessary to solve equation G-39 for the unknown x, y, z, V and t.

Solution procedures involve making an initial guess at the solution, and then minimizing the residual errors R_i. The errors for the first approximation x_0, y_0, z_0, V_0, t_0 are

$$\Delta x = x - x_0 \qquad\qquad \text{(G-40a)}$$

$$\Delta y = y - y_0 \qquad\qquad \text{(G-40b)}$$

$$\Delta z = z - z_0 \qquad\qquad \text{(G-40c)}$$

$$\Delta V = V - V_0 \qquad\qquad \text{(G-40d)}$$

$$\Delta t = t - t_0 \qquad\qquad \text{(G-40e)}$$

Successive approximations are improved by adding the errors from the preceding approximation.

$$\text{Improved} \quad x_0 = x_0 + \Delta x \qquad\qquad \text{(G-41a)}$$

$$\text{Improved} \quad y_0 = y_0 + \Delta y \qquad\qquad \text{(G-42a)}$$

$$\text{Improved} \quad z_0 = z_0 + \Delta z \qquad\qquad \text{(G-43a)}$$

$$\text{Improved} \quad V_0 = V_0 + \Delta V \qquad\qquad \text{(G-44a)}$$

$$\text{Improved} \quad t_0 = t_0 + \Delta t \qquad\qquad \text{(G-45a)}$$

This process is repeated until a minimum value of R_i is found. Minimizing the R_i involves a Taylor series expansion of equation G-39 followed by a differentiation with respect to the 5 unknown variables. This results in a set of 5 simultaneous normalized equations which are solved by successive approximations of improved estimates to converge to the solution.

This is a standard solution procedure used by seismologists in locating the foci of microearthquakes. The Bureau of Mines Denver Research Center is completing a report on an adaption of this type solution procedure for real-time microseismic systems. This forthcoming report will include the mathematical details and a computer program listing.

Generated Block Solutions

The generated block method is a quick reference system of predetermined exact source locations generated on a digital computer. The technique was developed so that source locations from arrival time data could be obtained in the field without a computer. To set up the method requires beforehand knowledge of the geophone coordinates, the average P-wave velocity, and the real time units of the printed arrival time data. The computer uses this information to determine the arrival time sequences that would be observed by the geophones for any point in a rock mass. The field data print out is then compared to the lists of predetermined sources to find the best matching arrival time sequences. The coordinates of this point are then the best estimate of the source coordinates.

This source location method, as well as previously described methods, can be solved using the computer program listed in Appendix H.

APPENDIX H. - COMPUTER PROGRAM FOR MICROSEISMIC DATA ANALYSIS

The real time source location computed by the microseismic monitoring system may be very close to the true source of the event or may be very inaccurate. In minewide monitoring, inaccuracies are caused by out-of-sequence arrival times, owing to simultaneous triggering of distant geophones by another event, mining noise, electrical noise, etc. To correct this improper data one must use an interactive computer and a data analysis computer program. Table H-1 is a computer program listing for microseismic data analysis. This program was written for a Data General NOVA minicomputer, hence requires modification, mainly I/O statements, for use on another computer. Figures H-1 to H-6 show flow charts of the main program and its subroutines.

Table H-2 presents a field example of using this program to correct data. The rock burst monitoring system printout is included. A glance at the geophone and arrival time sequence suggests that the X, Y, Z source location was bad, as is explained below. Program MASSAGE was called on an interactive minicomputer and the operator follows the typed instructions to check and correct the original source coordinates. The circled items are the operator entries to the program. Data analysis procedures are as-follows:

1) The X, Y, Z coordinates printed are for a large event, bump or small burst, occurring well out in the north wall at the east end of the mine on about the 7500 level. The first three geophones hit indicates the event occurred in the west end of the mine near the vein just above the 7700 level.

2) Program MASSAGE is typed into the computer and the computer responds by instructing the operator on how to enter any of the four subprograms used in checking or correcting microseismic data.

3) The operator decides that the event will be first checked by having the computer print out what the geophone sequence and arrival times would be if the event came from the listed source; hence, 3 is typed in for NDEX to use the GENBLK subprogram.

4) The computer prints out instructions for using GENBLK. The operator types in the coordinates of the event, specifying that data for only that point is to be printed out. The computer prints out the geophone numbers and arrival times. Comparison of this information with the original data confirms the operator's suspicion that the event was mislocated.

5) The operator scans the geophones hit and his map of geophone locations. It is immediately apparent that geophones 19, 20, and 17, on the east end of the mine, were hit by a different, essentially simultaneous, event.

6) The operator relocates the event using subprogram LQD, a least squares direct solution routine.

7) Having finished the GENBLK request the computer again asks for a value for NDEX. The operator types a 1 to enter the LQD routine.

8) Instructions are printed out, and the operator responds by typing in the number of geophones to be used and the geophone number and arrival time information, excluding geophones 19, 20 and 17. A corrected location is printed out. The low value for the standard deviation indicates the answer to be acceptable.

9) The operator accepts the solution and types a 0 to return to the main program.

10) The operator checks this solution using GENBLK, typing a 3 and entering the corrected coordinates. The resulting geophone sequence agrees perfectly with the corrected print out. However, the arrival time values indicate a lower field seismic velocity than the model velocity used in GENBLK.

11) The computer asks for its next instruction and the operator, having decided to determine the seismic velocities to geophones using subprogram SPVEL, types an NDEX value of 4.

12) The instructions for the use of SPVEL are followed. The corrected source coordinates are entered followed by the number of geophones and the geophone number and arrival time information.

13) The calculated seismic velocities to nearer geophones are slow, agreeing with the GENBLK observations. The average velocity appears to be about 15,800 feet per second.

14) The operator checks this result by entering a value of 2 for NDEX and simultaneously calculates both source coordinates and the best-average seismic velocity using subprogram LQDCV.

15) The operator follows the printed instructions by entering the number of geophones to be used and the geophone numbers and their arrival times. These newly calculated source coordinates closely agree to the previous LQD solution. The computed average P-wave velocity agrees with the SPVEL results, and the standard deviation indicates the solutions are good.

16) The operator corrects the original event coordinates and types a 0 to terminate the program.

This example demonstrates specific uses of the computer program. Other applications, such as determining seismic velocities from test blast data, testing potential geophone locations using GENBLK, generating lists of solutions for specific blocks using GENBLK, can be readily executed.

```
C
C          PROGRAM TO MASSAGE DATA TO GET BEST FIT AND/OR SEISMIC VELOCITY
C
           COMMON/LB/ IC(24,3)
           TYPE" PROGRAM TO IMPROVE SOLUTION OR TO GET SEISMIC VELOCITY"
           TYPE" PROGRAM OPERATES UNDER NDEX CODE<15>"
           TYPE"NDEX=1,2,3,4,5 - 1=LSQD,2=LSQDCV,3=GBLK,4=PVEL,5=STOP"
        1  ACCEPT" TYPE IN VALUE OF NDEX", NDEX
           GO TO (2,3,4,5,6),NDEX
        2  CALL LQD
           GO TO 1
        3  CALL LQDCV
           GO TO 1
        4  CALL GENBLK
           GO TO 1
        5  CALL SPVEL
           GO TO 1
        6  STOP
           END

C
           SUBROUTINE LQD
           COMMON/LB/ IC(3,24)
           DIMENSION IFO(24),ITIM(24),ABC(24,3),ANGLE(24,3),DS(24),
          1 FL(24),BUAN(3),ABCCO(24,3),H(24),SLET(4),AA(9),BB(3),B(3)
           CALL GCORD8
C
        1  TYPE "LEAST SQUARED DIRECT SOLUTION PROGRAM FOR CHECKING EVENTS
          1 <15>"," ENTER NUMBER OF GEOPHONES  FOR LEAST SQUARES
          2 <15>"," SEPARATE BY COMMAS - TYPE 0 TO END <15>"
           ACCEPT NG
```

```
      NHIT=NG
      IF(NG)900,900,2
    2 CONTINUE
      TYPE "ENTER GEOPHONE AND ARRIVAL TIMES  SEPARATE BY COMMAS<15>"
      ACCEPT (IFO(I),ITIM(I), I=1,NG)
      DO 10 I=1,NHIT
      J=IFO(I)
      DO 10 K=1,3
   10 ABC(I,K)=FLOAT(IC(K,J))
      DO 21 K=1,9
   21 AA(K)=0.0
      DO 22 K=1,3
   22 BB(K)=0.0
      DO 36 I=2,NHIT
      DS(I)=.95*FLOAT(ITIM(I))
      CO=0.0
      DO 14 K=1,3
      ANGLE(I,K)=ABC(1,K)-ABC(I,K)
   14 CO=CO+ABC(1,K)**2-ABC(I,K)**2
      FL(I)=DS(I)**2+CO
      IF(I-2)13,15,36
   15 BUFL=FL(I)/DS(I)
   36 CONTINUE
      TT=0.0
      DO 13 I=3,NHIT
      DO 16 K=1,3
   16 BUAN(K)=ANGLE(2,K)/DS(2)
      ST=0.0
      H(I)=BUFL-FL(I)/DS(I)
      DO 18 K=1,3
      ABCCO(I,K)=(BUAN(K)-ANGLE(I,K)/DS(I))*2.
   18 ST=ST+ABCCO(I,K)**2
      DEN=SQRT(ST)
      DO 20 K=1,3
   20 SLET(K)=ABCCO(I,K)/DEN
      SLET(4)=H(I)/DEN
      TT=TT+SLET(4)*SLET(4)
```

(Note: The .95 constant comes from multiplying the seismic velocity times the factor to convert arrival times to seconds - 19000 x .00005)

```
      DO 24 M=1,3
      DO 24 N=1,3
      INC=3*(M-1)+N
   24 AA(INC)=AA(INC)+SLET(N)*SLET(M)
      DO 25 N=1,3
      BB(N)=BB(N)+SLET(N)*SLSET(4)
   25 B(N)=BB(N)
   13 CONTINUE
      CALL SIMQ(AA,BB,3,KS)
      IF(KS)100,100,101
  101 TYPE"<14>","      MATRIX IS SINGULAR <15>"
      GO TO 1
  100 CONTINUE
      SE=SQRT((TT-BB(1)*B(1)-BB(2)*B(2)-BB(3)*B(3))/FLOAT(NHIT-5))
      TYPE"<14>","        LEAST SQUARED SOLUTION FOR EVENT <15>"
      WRITE(10,11) BB(1),BB(2),BB(3),NHIT,SE
   11 FORMAT(1H0,2X,3H X=,F6.0,2X,3H Y=,F6.0,2X,3H Z=,F7.0,4X, 4H NG=,I3,
     120H STANDARD DEVIATION=,F7.1)
      GO TO 1
  900 RETURN
      END


   C
   C   THIS SUBPROGRAM SUPPLIES THE STAR GEOPHONE COORDINATES 2/13/80
   C
   C
      SUBROUTINE GCORD8
      COMMON/LB/ IC(3,24)
      DATA IC/        1696, 466, -925,2041, 381, -922,1526, 313,-1327,
     12132, 671,-1322, 925, 719,-2119, 953, 998,-2123,1617, 596,-1130,
     21155, 936,-2125,1744, 459,-1132,1325, 690,-2127,2150, 550,-1525,
     3 690,1055,-1731, 742, 853,-1730, 890,1003,-1732,1128, 854,-1732,
     41401, 826,-1734,1531, 504,-1732,1397, 193,-1735,2041, 535,-1129,
     52134  711,-1129,1030, 850,-1926, 818, 818,-1932, 720,1019,-1922,
                    1937/
```

```
C       SUBROUTINE TO SOLVE SIMULTANEOUS EQUATIONS
        SUBROUTINE SIMQ(A,B,N,KS)
        DIMENSION A(16),B(4)
C       FORWARD SOLUTION
        TOL=0.0
        KS=0
        JJ=-N
        DO 65 J=1,N
        JY=J+1
        JJ=JJ+N+1
        BIGA=0.0
        IT=JJ-J
        DO 30 I=J,N
C         SEARCH FOR MAXIMUM COEFFICIENT IN COLUMN
        IJ=IT+I
        IF(ABS(BIGA)-ABS(A(IJ)))20,30,30
   20   BIGA=A(IJ)
        IMAX=I
   30   CONTINUE
C       TEST FOR PIVOT LESS THAN TOLERANCE OF SINGULAR MATRIX
        IF(ABS(BIGA)-TOL)35,35,40
   35   KS=1
        RETURN
C         INTERCHANGE ROWS IF NECESSARY
   40   I1=J+N*(J-2)
        IT=IMAX-J
        DO 50 K=J,N
        I1=I1+N
        I2=I1+IT
        SAVE=A(I1)
        A(I1)=A(I2)
        A(I2)=SAVE
```

```
C       DIVIDE EQUATION BY LEADING COEFFICIENT
50  A(IJ)=A(IJ)/BIGA
    SAVE=B(IMAX)
    B(IMAX)=B(J)
    B(J)=SAVE/BIGA
C       ELIMINATE NEXT VARIABLE
    IF(J-N)55,70,55
55  IQS=N*(J-1)
    DO 65  IX=JY,N
    IXJ=IQS+IX
    IT=J-IX
    DO 60  JX=JY,N
    IXJX=N*(JX-1)+IX
    JJX=IXJX+IT
60  A(IXJX)=A(IXJX)-(A(IXJ)*A(JJX))
65  B(IX)=B(IX)-(B(J)*A(IXJ))
C       BACK SOLUTION
70  NY=N-1
    IT=N*N
    DO 80  J=1,NY
    IA=IT-J
    IB=N-J
    IC=N
    DO 80  K=1,J
    B(IB)=B(IB)-A(IA)*B(IC)
    IA=IA-N
80  IC=IC-1
    RETURN
    END
```

```
C
        SUBROUTINE LQDCV
        COMMON/LB/ IC(3,24)
        DIMENSION IFO(24),ITIM(24),ABC(24,3),ANGLE(24,3),DS(24),
       1 FL(24),B(4),BUAN(3),ABCCO(24,3),H(24),SLET(5),AA(16),BB(4)
        CALL GCORDS
C
      1 TYPE "LEAST SQUARED DIRECT SOLUTION PROGRAM WITH CONSTANT VELOCITY
       1 <15>"," ENTER NUMBER OF GEOPHONES FOR LEAST SQUARES
       2 <15>"," SEPARATE BY COMMAS - TYPE 0 TO END <15>"
        ACCEPT NG
        NHIT=NG
        IF(NG)900,900,2
      2 CONTINUE
        TYPE "ENTER GEOPHONE AND ARRIVAL TIMES  SEPARATE BY COMMAS<15>"
        ACCEPT (IFO(I),ITIM(I), I=1,NG)
        DO 10 I=1,NHIT
        J=IFO(I)
        DO 10 K=1,3
     10 ABC(I,K)=FLOAT(IC(K,J))
        DO 21 K=1,16
     21 AA(K)=0.0
        DO 22 K=1,4
     22 BB(K)=0.0
        DO 36 I=2,NHIT
        DS(I)=.00005*FLOAT(ITIM(I))
        CO=0.0
        DO 14 K=1,3
        ANGLE(I,K)=ABC(1,K)-ABC(I,K)
     14 CO=CO+ABC(1,K)**2-ABC(I,K)**2
        FL(I)=CO
        IF(I-2)13,15,36
     15 BUFL=FL(I)/DS(I)
     36 CONTINUE
        TT=0.0
        DO 13 I=3,NHIT
        DO 16 K=1,3
     16 BUAN(K)=ANGLE(2,K)/DS(2)
```

(Note: .00005 is factor to convert the arrival times to seconds.)

```
      ST=0.0
      H(I)=BUFL-FL(I)/DS(I)
      DO 18 K=1,3
      ABCCO(I,K)=(BUAN(K)-ANGLE(I,K)/DS(I))*2.
   18 ST=ST+ABCCO(I,K)**2
      DEN=SQRT(ST)
      DO 20 K=1,3
   20 SLET(K)=ABCCO(I,K)/DEN
      SLET(4)=(DS(2)-DS(I))/DEN
      SLET(5)=H(I)/DEN
      TT=TT+SLET(5)*SLET(5)
      DO 24 M=1,4
      DO 24 N=1,4
      INC=4*(M-1)+N
   24 AA(INC)=AA(INC)+SLET(N)*SLET(M)
      DO 25 N=1,4
       BB(N)=BB(N)+SLET(N)*SLET(5)
   25 B(N)=BB(N)
   13 CONTINUE
      DO 26 M=1,4
      N=12+M
   26 AA(N)=-AA(N)
      CALL SIMQ(AA,BB,4,KS)
      IF(KS)100,100,101
  101 TYPE"<14>","      MATRIX IS SINGULAR <15>"
      GO TO 1
  100 CONTINUE
      SE=SQRT((TT-BB(1)*B(1)-BB(2)*B(2)-BB(3)*B(3)+BB(4)*B(4))
     1/FLOAT(NHIT-6))
      BB(4)=SQRT(BB(4))
      TYPE"<14>","        LEAST SQUARED SOLUTION FOR EVE'
      WRITE(10,11) BB(1),BB(2),BB(3),BB(4),NHIT,SE
   11 FORMAT(1H0,2X,3H X=,F6.0,2X,3H Y=,F6.0,2X,3H Z=,
     1F7.0, 4H NG=I3,11H  STD DEV =F7.1,///)
      GO TO 1
  900 RETURN
      END
```

```
C
C      PROGRAM GBLK - CALCULATE AND PRINT OUT SIMULATED EVENTS FOR COMPARISON
C

       SUBROUTINE GENBLK
       COMMON/LB/ IC(3,24)
       DIMENSION D(24),T(24),IT(24),JJ(24)
C

       CALL GCORD8
       TYPE "PROGRAM TO CREATE BLOCK POINT SOLUTIONS FOR COMPARISON WITH
      1RBM EVENTS <15>","ENTER X,Y,Z STARTING COORDINATES, X,Y,Z ENDING C
      2OORDINATES, BLOCK INCREMENT, AND END JOB TEST <15>","SEPARATE DATA
      3 COMMAS AND HIT RETURN.   TO END JOB KEY IN 1,1,1,1,1,1,1,1 <15>"
   18 ACCEPT XS,YS,ZS,XL,YL,ZL,DINC,NDX
       TYPE "<14>"
       TYPE "                        BEGINNING NEW BLOCK <15>"
       Z=ZS
   20 Y=YS
   21 X=XS
   22 CONTINUE
       TMIN=8000.
       JJ(1)=X
       JJ(2)=Y
       JJ(3)=Z
       DO 5 J=1,24
       D(J)=0.0
       DO 7 K=1,3
    7 D(J)=D(J)+(FLOAT(IC(K,J)-JJ(K)))**2
       D(J)=SQRT(D(J))
       T(J)=D(J)/(19000.*.00005)
    5 TMIN=AMIN1(TMIN,T(J))
       DO 6 J=1,24
    6 T(J)=T(J)-TMIN
       NS=24
       DO 91 J=1,NS
   91 JJ(J)=J
```

(Note: 19000 is the seismic velocity and
.00005 converts seconds to machine units.)

```
92  CONTINUE
    DO 93 J=2,NS
    IF(T(J-1)-T(J))93,93,94
94  TEMP=T(J)
    T(J)=T(J-1)
    T(J-1)=TEMP
    JS=JJ(J)
    JJ(J)=JJ(J-1)
    JJ(J-1)=JS
93  CONTINUE
    NS=NS-1
    IF(NS-2)95,95,92
95  CONTINUE

96  DO 96 J=1,24
    IT(J)=T(J)
    IX=X
    IY=Y
    IZ=Z
    WRITE(10,11) IX,IY,IZ,(JJ(I),I=1,12)
11  FORMAT(3I5,I4,22I5)
    WRITE(10,12)(IT(I),I=1,12)
12  FORMAT(14X,23I5)
    TYPE "<15>"
    X=X+DINC
    IF(X-XL)22,22,26
26  Y=Y+DINC
    IF(Y-YL)21,21,27
27  Z=Z+DINC
    IF(Z-ZL)20,20,28
28  CONTINUE
    IF(NDX)18,18,10
10  RETURN
    END
```

C

```
C
C     THIS PROGRAM COMPUTES P-WAVE VELOCITIES FROM BLAST DATA
C
      SUBROUTINE SPVEL
      COMMON/LB/ IC(3,24)
      DIMENSION BC(3),S(24),D(24),TT(24),U(24)
      CALL GCORDS
1     TYPE "(14)"
      TYPE "PROGRAM TO COMPUTE SEISMIC VELOCITIES FROM BLASTING DATA.
     1(15)"," USES STAR GEOPHONE COORDINATES AS OF 6/15/79 UPDATE CHANGES
     2(15)"," ENT X,Y,Z COORDINATES OF BLAST POINT AND THE NUMBER OF GEO
     3PHONES - ALL SEPARATED BY COMMAS.(15)"," TO END JOB TYPE 0,0,0,0
     4 AND HIT RETURN.(15)"
      ACCEPT BC(1),BC(2),BC(3),NG
      IF(BC(1))4,43,4
4     DO 7 I=1,24
      D(I)=0.0
      DO 9 K=1,3
9     D(I)=D(I)+(FLOAT(IC(K,I))-BC(K))**2
      D(I)=SQRT(D(I))
7     S(I)=-1.
C
      TYPE "ENTER THE GEOPHONE AND ARRIVAL TIME DATA AS ON THE RBM PRINT
     1OUT(15)"," SEPARATE THE DATA BY COMMAS AND HIT RETURN TO GO(15)"
      DO 8 I=1,NG
      ACCEPT M,S(M)
8     CONTINUE
      DO 10 I=1,24
      IF(S(I))10,11,10
11    MM=I
      GO TO 13
10    CONTINUE
```

```
13 M=0
   TII=0.0
    DO 14 I=1,24
   TT(I)=D(I)-D(MM)
   IF(S(I))14,14,15
15 V(I)=TT(I)/(S(I)*.00005)
   M=M+1
   TT(I)=D(I)/(V(I)*.00005)-S(I)
   TII=TII+TT(I)
14 CONTINUE
   SP=TII/FLOAT(M)
   DO 57 I=1,24
   IF(S(I))58,17,17
58 V(I)=0.0
   GO TO 57
17 V(I)=D(I)/((S(I)+SP)*.00005)
57 CONTINUE
C

   WRITE (10,16) BC(1),BC(2),BC(3)
16 FORMAT(1H1,10X,26HTEST BLAST LOCATION WAS X=,F6.0,3H Y=,F6.0,2HZ=,
  1F6.0/33H0   SEISMIC VELOCITY TO GEOPHONES/51H0     GEOPHONE
  2 P-VELOCITY          DISTANCE /)
   WRITE(10,6) (I,V(I),D(I), I=1,24)
 6 FORMAT(1H0,I10,11X,F10.0,11X,F7.0)
   GO TO 1
48 CONTINUE
   RETURN
   END
```
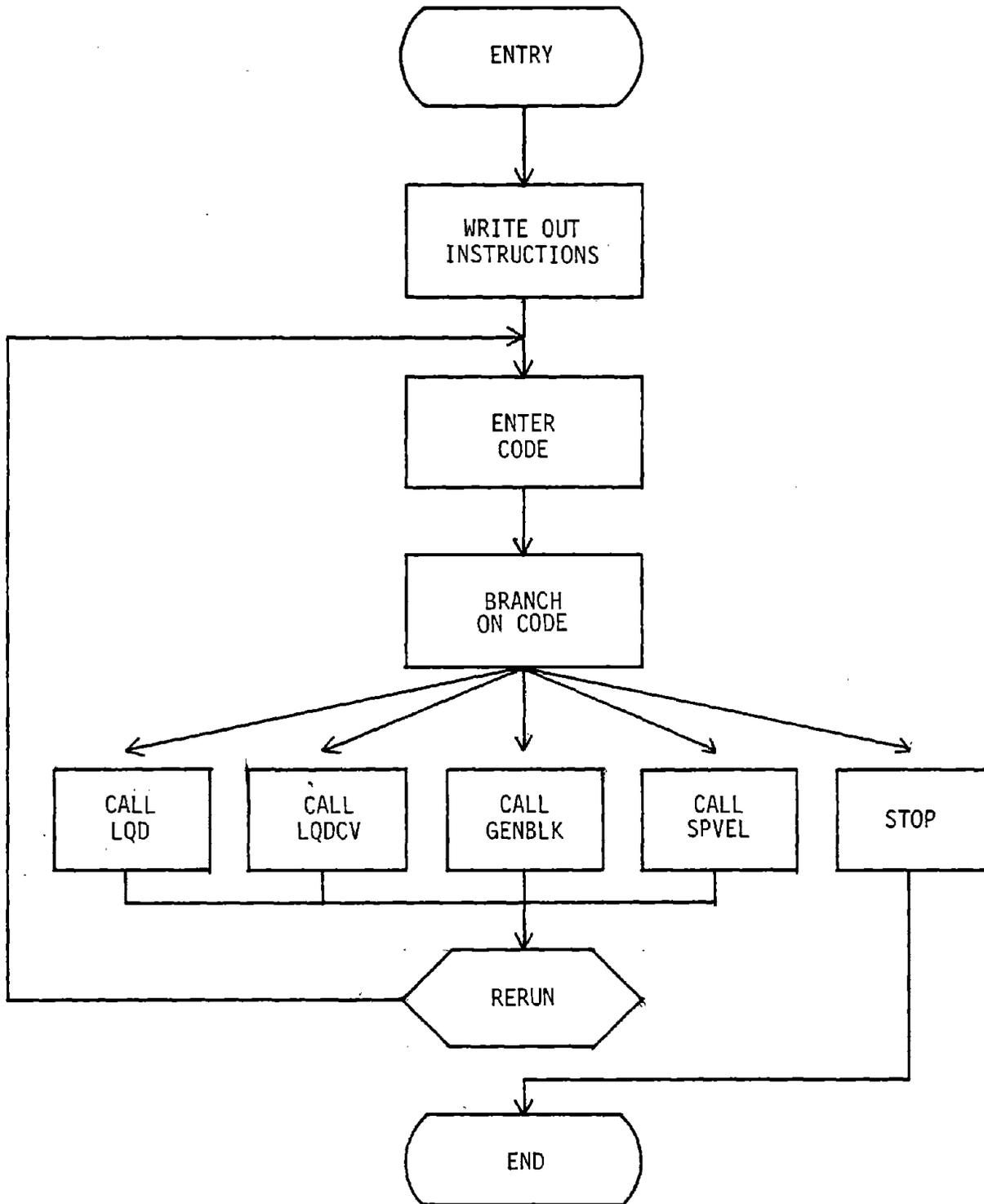
(Note: .00005 converts machine unit arrival times to seconds)

FIGURE H-1— PROGRAM MASSAGE

```
                    ENTRY
                      │
                      ▼
              ┌─────────────────┐
              │  CALL GCORD8     │
              │      FOR         │
              │  GEO. COORDS.    │
              └─────────────────┘
                      │
                      ▼
              ┌─────────────────┐
        ┌────▶│   WRITE OUT      │
        │     │  INSTRUCTIONS    │
        │     └─────────────────┘
        │             │
        │             ▼
        │     ┌─────────────────┐
        │     │     ENTER        │
        │     │  NO. GEOPHONES   │
        │     └─────────────────┘
        │             │
        │             ▼
        │          ◇ LAST ◇   YES
        │          ◇ RUN? ◇──────────────┐
        │             │                  │
        │             │ NO               │
        │             ▼                  │
        │     ┌─────────────────┐        │
        │     │   WRITE OUT      │        │
        │     │  INSTRUCTIONS    │        │
        │     └─────────────────┘        │
        │             │                  │
        │             ▼                  │
        │     ┌─────────────────┐        │
        │     │     ENTER        │        │
        │     │ GEOPHONES AND    │        │
        │     │  ARRIVAL TIMES   │        │
        │     └─────────────────┘        │
        │             │                  │
        │             ▼                  │
        │     ┌─────────────────┐        │
        │     │  FORM MATRIX     │        │
        │     │  COMPONENTS      │        │
        │     └─────────────────┘        │
        │             │                  │
        │             ▼                  │
        │     ┌─────────────────┐        │
        │     │   CALL SIMQ      │        │
        │     │    SOLVE         │        │
        │     │  EQUATIONS       │        │
        │     └─────────────────┘        │
        │             │                  │
        │             ▼                  │
        │     ┌─────────────────┐        │
        │     │  CALCULATE       │        │
        │     │ STANDARD DEVIATION│       │
        │     └─────────────────┘        │
        │             │                  │
        │             ▼                  │
        │        ⬡ WRITE ⬡               │
        └────────⬡ X,Y,Z,SD ⬡◀──────────┘
                      │
                      ▼
                   RETURN
```
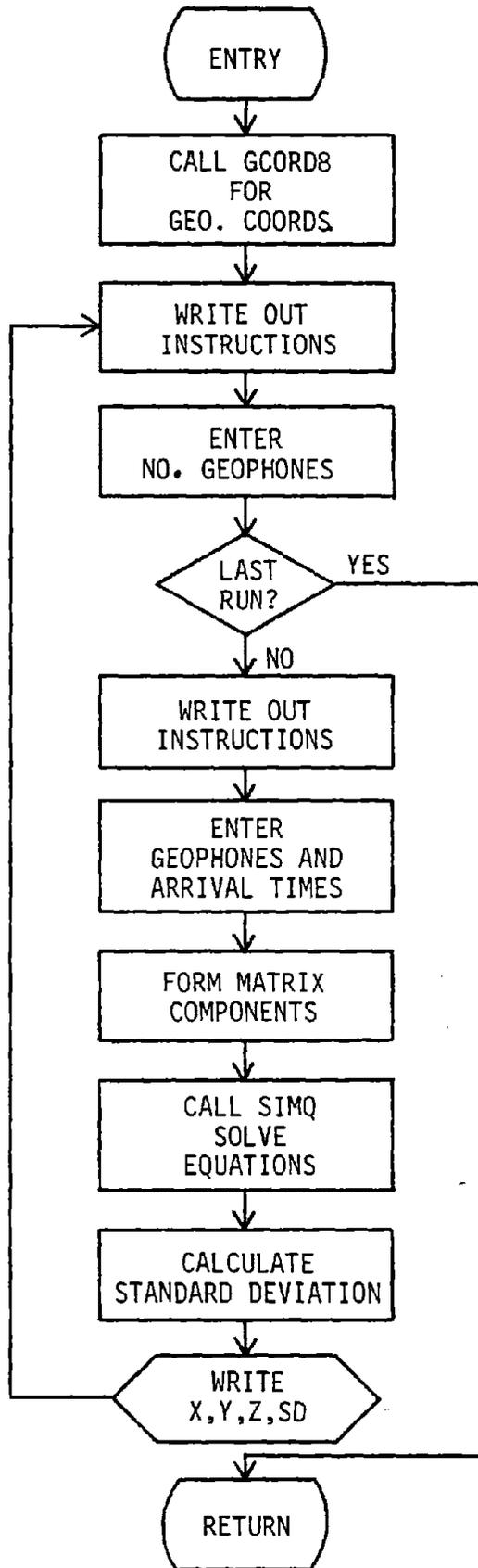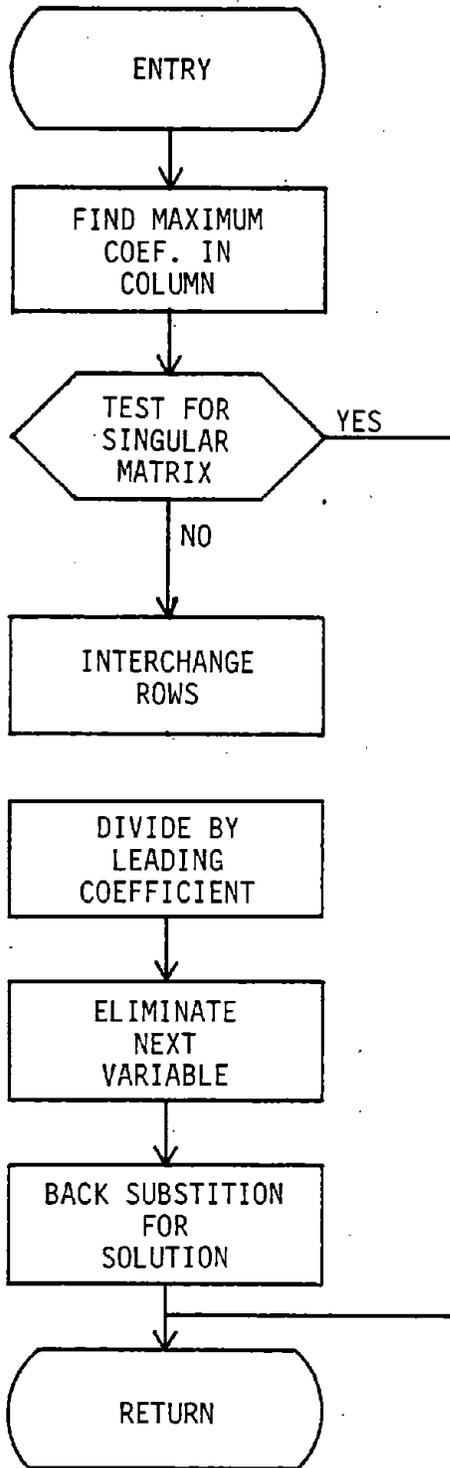
FIGURE H-2— SUBROUTINE LQD

FIGURE H-3— SUBROUTINE SIMQ
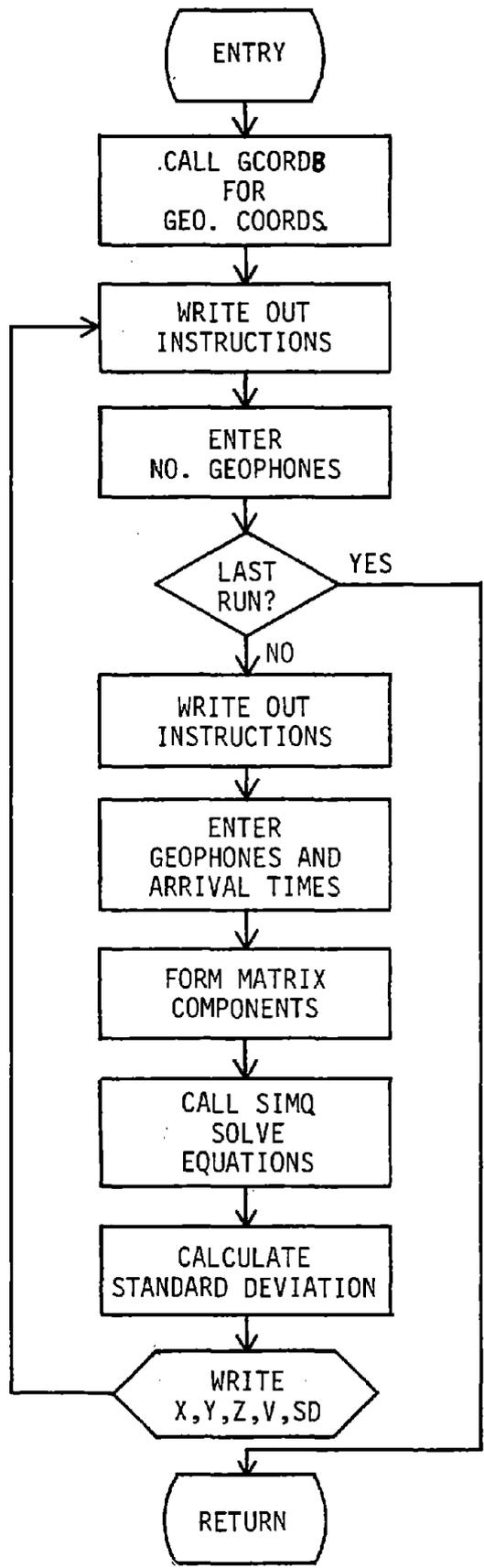
FIGURE H-4— SUBROUTINE LQDCV
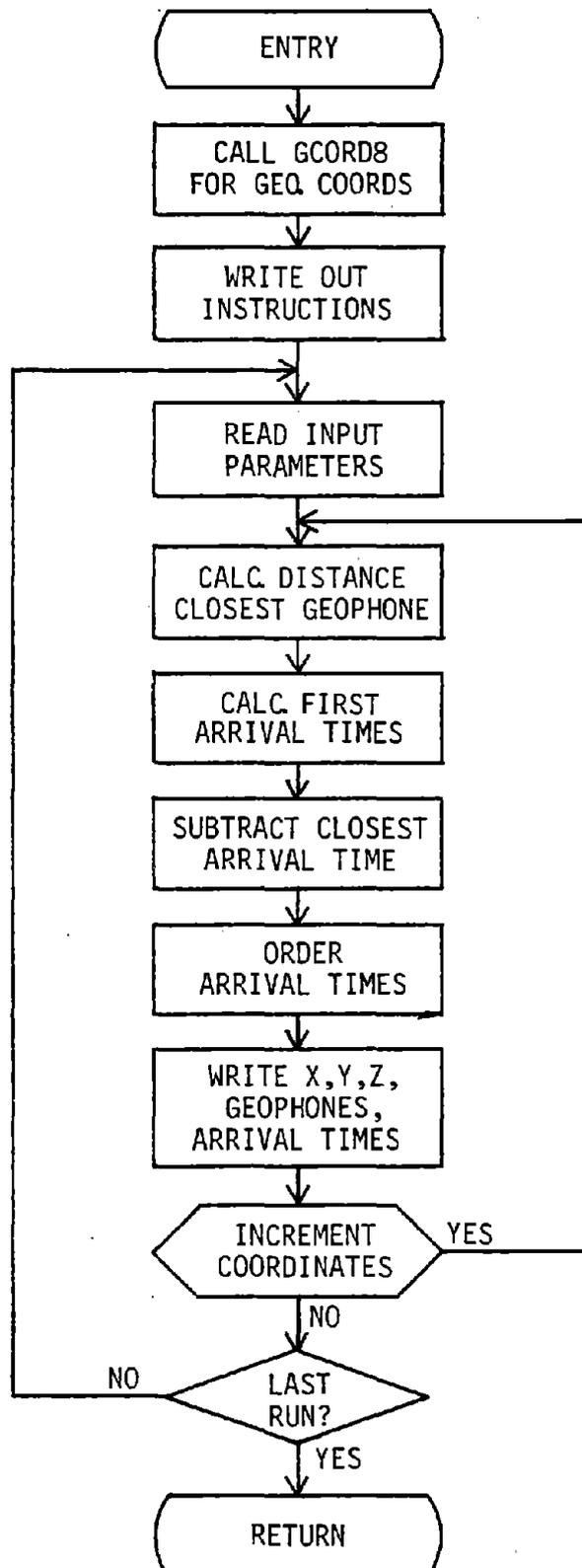
FIGURE H-5—SUBROUTINE GENBLK

```
                    ┌──────────────┐
                    │    ENTRY     │
                    └──────┬───────┘
                           │
                    ┌──────▼───────┐
                    │ CALL GCORD8  │
                    │FOR GEO.COORDS│
                    └──────┬───────┘
                           │
                    ┌──────▼───────┐
          ┌────────▶│  WRITE OUT   │
          │         │ INSTRUCTIONS │
          │         └──────┬───────┘
          │                │
          │         ┌──────▼───────┐
          │         │ ENTER BLAST  │
          │         │ COORDINATES, │
          │         │ NO.GEOPHONES │
          │         └──────┬───────┘
          │                │
          │           ╱────▼────╲        YES
          │          ◁ LAST RUN? ▷───────────────┐
          │           ╲─────────╱                │
          │                │ NO                   │
          │         ┌──────▼───────┐              │
          │         │CALC.DISTANCES│              │
          │         │ TO GEOPHONES │              │
          │         └──────┬───────┘              │
          │                │                      │
          │         ┌──────▼───────┐              │
          │         │  WRITE OUT   │              │
          │         │ INSTRUCTIONS │              │
          │         └──────┬───────┘              │
          │                │                      │
          │         ┌──────▼───────┐              │
          │         │  ENTER GEO.& │              │
          │         │ ARRIVAL TIMES│              │
          │         └──────┬───────┘              │
          │                │                      │
          │         ┌──────▼───────┐              │
          │         │ FIND CLOSEST │              │
          │         │   GEOPHONE   │              │
          │         └──────┬───────┘              │
          │                │                      │
          │         ┌──────▼───────┐              │
          │         │ CALC.INITIAL │              │
          │         │  P.VELOCITY  │              │
          │         └──────┬───────┘              │
          │                │                      │
          │         ┌──────▼───────┐              │
          │         │  CALC.BEST   │              │
          │         │  SHOT TIME   │              │
          │         └──────┬───────┘              │
          │                │                      │
          │         ┌──────▼───────┐              │
          │         │  CALCULATE   │              │
          │         │ P.VELOCITIES │              │
          │         └──────┬───────┘              │
          │                │                      │
          │         ┌──────▼───────────┐          │
          │         │WRITE BLAST COORDS,│         │
          └─────────┤ GEOS, P.VELOCITIES│         │
                    │   & DISTANCES    │          │
                    └──────┬───────────┘          │
                           │                      │
                    ┌──────▼───────┐◀─────────────┘
                    │    RETURN    │
                    └──────────────┘
```
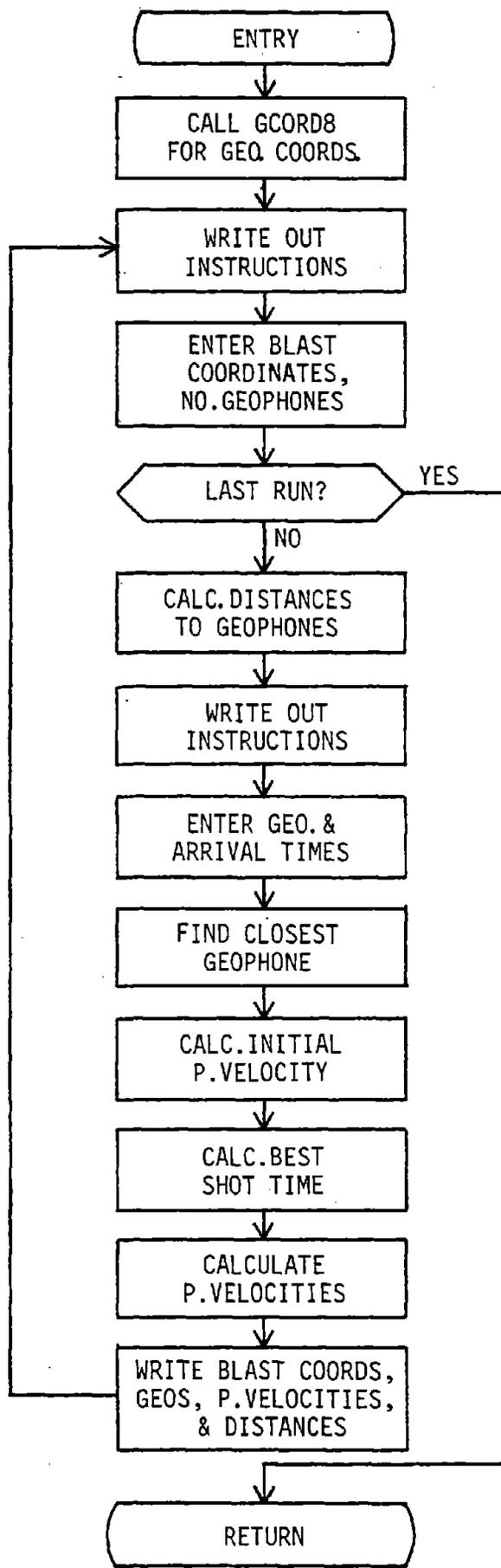
FIGURE H-6— SUBROUTINE SPVEL

-196-

X	Y	Z	Year	Day	Hr	Mn	Sc
1664	1340	-1569	1978	195	20	33	46

GEO TIME   ENERGY 743

GEO	TIME
22	0
13	9
23	18
19	66
12	106
14	125
20	157
21	214
17	273
15	281

(MASSAGE)   (Note: Circled items are the operator response.)
PROGRAM TO IMPROVE SOLUTION OR TO GET SEISMIC VELOCITY
PROGRAM OPERATES UNDER NDEX CODE

NDEX=1,2,3,4,5 - 1=LSQD,2=LSQDCV,3=GBLK,4=PVEL,5=STOP
 TYPE IN VALUE OF NDEX(3)
PROGRAM TO CREATE BLOCK POINT SOLUTIONS FOR COMPARISON WITHRBM EVENTS
ENTER X,Y,Z STARTING COORDINATES, X,Y,Z ENDING COORDINATES, BLOCK INCREMENT, AND
SEPARATE DATA COMMAS AND HIT RETURN.   TO END JOB KEY IN 1,1,1,1,1,1,1,1

(1664,1340,-1569,1664,1340,-1569,1,1)
                   BEGINNING NEW BLOCK

1664	1340	-1569	16	15	4	8	14	17	7	21	24	10	11	6
			0	148	265	268	272	275	278	291	329	337	345	382

TYPE IN VALUE OF NDEX⓪
LEAST SQUARED DIRECT SOLUTION PROGRAM FOR CHECKING EVENTS
ENTER NUMBER OF GEOPHONES FOR LEAST SQUARES
SEPARATE BY COMMAS - TYPE 0 TO END

⑦
ENTER GEOPHONE AND ARRIVAL TIMES SEPARATE BY COMMAS

22,0
13,9
23,18
12,106
14,125
21,214
15,281

X= 743.   Y= 893.   Z= -1859.   NG= 7 STANDARD DEVIATION= 2.5
LEAST SQUARED DIRECT SOLUTION PROGRAM FOR CHECKING EVENTS
ENTER NUMBER OF GEOPHONES FOR LEAST SQUARES
SEPARATE BY COMMAS - TYPE 0 TO END

⓪

TYPE IN VALUE OF NDEX③
PROGRAM TO CREATE BLOCK POINT SOLUTIONS FOR COMPARISON WITHRBM EVENTS
ENTER X,Y,Z STARTING COORDINATES, X,Y,Z ENDING COORDINATES, BLOCK INCREMENT, AND
SEPARATE DATA COMMAS AND HIT RETURN.   TO END JOB KEY IN 1,1,1,1,1,1,1

743,893,-1859,743,893,-1859,1,1
BEGINNING NEW BLOCK

| 743 | 893-1859 | 22 | 13 | 23 | 12 | 14 | 21 | 6 | 5 | 15 | 24 | 8 | 10 |
| | | 0 | 6 | 14 | 88 | 99 | 177 | 236 | 245 | 293 | 355 | 382 | 571 |

TYPE IN VALUE OF NDEX④
PROGRAM TO COMPUTE SEISMIC VELOCITIES FROM BLASTING DATA.
USES STAR GEOPHONE COORDINATES AS OF 6/15/79 UPDATE CHANGES
ENT X,Y,Z COORDINATES OF BLAST POINT AND THE NUMBER OF GEOPHONES - ALL SEPARATE
TO END JOB TYPE 0,0,0,0 AND HIT RETURN.

743,893,-1859,7

ENTER THE GEOPHONE AND ARRIVAL TIME DATA AS ON THE RBM PRINTOUT
 SEPARATE THE DATA BY COMMAS AND HIT RETURN TO GO

22,0
13,9
23,18
12,106
14,125
21,214
15,281

TEST BLAST LOCATION WAS X= 743. Y= 893.Z=-1859.

SEISMIC VELOCITY TO GEOPHONES

GEOPHONE	P-VELOCITY	DISTANCE
1	0.	1401.
2	0.	1681.
3	0.	1110.
4	0.	1506.
5	0.	362.
6	0.	353.

7	0.	1176.
8	0.	492.
9	0.	1311.
10	0.	672.
11	0.	1486.
12	15882.	213.
13	15757.	135.
14	15534.	223.
15	18369.	407.
16	0.	673.
17	0.	888.
18	0.	966.
19	0.	1532.
20	0.	1675.
21	15824.	298.
22	15854.	129.
23	15822.	143.
24	0.	467.

PROGRAM TO COMPUTE SEISMIC VELOCITIES FROM BLASTING DATA.
USES STAR GEOPHONE COORDINATES AS OF 6/15/79 UPDATE CHANGES
ENT X,Y,Z COORDINATES OF BLAST POINT AND THE NUMBER OF GEOPHONES - ALL SEPARATE
TO END JOB TYPE 0,0,0,0 AND HIT RETURN.

0,0,0,0

TYPE IN VALUE OF NDEX(2)
LEAST SQUARED DIRECT SOLUTION PROGRAM WITH CONSTANT VELOCITY
 ENTER NUMBER OF GEOPHONES FOR LEAST SQUARES
 SEPARATE BY COMMAS - TYPE 0 TO END

(7)
ENTER GEOPHONE AND ARRIVAL TIMES SEPARATE BY COMMAS

22.0
13.9
23.18
12.106
14.125
21.214
15.281

      X= 741.   Y= 898.   Z= -1858.   V= 15836. NG= 7 STD DEV =   1.3

LEAST SQUARED DIRECT SOLUTION PROGRAM WITH CONSTANT VELOCITY
 ENTER NUMBER OF GEOPHONES FOR LEAST SQUARES
 SEPARATE BY COMMAS - TYPE 0 TO END

(0)
TYPE IN VALUE OF NDEX(5)
STOP

TYPE IN VALUE OF NDEX②
LEAST SQUARED DIRECT SOLUTION PROGRAM WITH CONSTANT VELOCITY
 ENTER NUMBER OF GEOPHONES FOR LEAST SQUARES
 SEPARATE BY COMMAS - TYPE 0 TO END

⑦

ENTER GEOPHONE AND ARRIVAL TIMES   SEPARATE BY COMMAS

22,0
13,9
23,18
12,106
14,125
21,214
15,281

     X= 741.   Y= 898.   Z= -1858.   V= 15836. NG= 7 STD DEV =   1.3

LEAST SQUARED DIRECT SOLUTION PROGRAM WITH CONSTANT VELOCITY
 ENTER NUMBER OF GEOPHONES FOR LEAST SQUARES
 SEPARATE BY COMMAS - TYPE 0 TO END

⓪
TYPE IN VALUE OF NDEX⑤
STOP

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