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THE COLLEGE OF EARTH AND MINERAL SCIENCES

FINAL REPORT

"Microseismic Techniques Applied to Coal Mine Safety"

USBM Grant No. G0101743 (MIN-45)

Dr. H. Reginald Hardy, Jr.
Principal Investigator

March 31, 1974

DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
WASHINGTON, D. C.

THE PENNSYLVANIA STATE UNIVERSITY

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"Microseismic Techniques Applied to Coal Mine Safety"

USBM Grant No. G0101743 [MIN-45]
Reporting Period: June 15, 1970 - March 31, 1974

Dr. H. Reginald Hardy, Jr.
Principal Investigator

DEPARTMENT OF MINERAL ENGINEERING

THE PENNSYLVANIA STATE UNIVERSITY

March 31, 1974

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ABSTRACT

This report describes the results of a research project carried out to investigate the feasibility of using transducer arrays, located on surface or in shallow boreholes, above an active coal mine to detect and locate the source of underground microseismic activity which normally occurs during mining.

The initial stage of the project involves the design and development of a self-contained mobile microseismic monitoring facility capable of use in remote field locations. Following this a variety of transducers, and transducer field installation techniques were investigated to obtain optimum sensitivity and high signal-to-noise characteristics. Preliminary efforts were also undertaken to develop semi-automated techniques for analysis of microseismic field data.

Using the facilities and techniques developed field studies were carried out at a number of surface locations over a central Pennsylvania coal mine operating at depths of the order of 500 feet. In particular studies were conducted over a previously mined development area, troubled by extensive problems of roof instability, and over two longwall panels during mining. Although many of the field studies were carried out during the development stage of the project, results in general have been most encouraging. Limited results were obtained over the development area, however excellent microseismic signals, correlating with underground strata instability, were detected over both longwall areas, proving the general feasibility of surface monitoring techniques. More recent studies, carried out as part of a subsequent project, and utilizing modified geophone installation techniques at a third longwall site, have verified explicitly the feasibility of measuring underground microseismic activity from surface locations.

Sections of typical field data are included in this report along with a brief review of the studies carried out at each of the field sites. Detailed analysis of data obtained at the second and third longwall test sites will be presented in a later report.

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INTRODUCTION

Mine Safety has always been a prime concern of the U. S. Bureau of Mines, and over the years much of their in-house research has been directed towards reduction of accidents and health hazards associated with the mining industry. As a consequence of the 1969 Coal Mine Health and Safety Bill, additional funds became available to the U. S. Bureau of Mines for support of outside research at industrial and educational institutions. Since the Spring of 1970 a number of such research projects have been underway at The Pennsylvania State University.

This document is the final project report on research carried out to investigate "Microseismic Techniques Applied to Coal Mine Safety" funded under Grant G0101743 (MIN-45) from the U. S. Bureau of Mines. The project was originally funded for a two year period starting June 15, 1970, followed by a one and one-half month no-cost extension to July 31, 1972. A one year project extension with additional funds was obtained August 1, 1972, and a final eight month no-cost extension was obtained August 1, 1973. The project has, therefore, spanned the period June 15, 1970, to March 31, 1974--a total of forty five and a half months.

Until recently there has been relatively little application of microseismic techniques in North American coal mines or in highly mechanized coal mines elsewhere, although there is little doubt that techniques based on microseismic activity rank amongst the most promising for the study of stability of underground structures. During the last few years microseismic techniques have been applied with increasing success to stability problems in open-pits and underground hard rock mines. Considerable applied, as well as basic, research has been carried out during this period and with the advent of highly reliable and sophisticated instrumentation for monitoring and recording microseismic activity, the technique has come of age.

From a mine safety point of view it would appear that microseismic techniques will be invaluable in the detection and location of poor roof conditions and overstressed pillars; two dangerous situations one now has little knowledge of until an actual failure occurs. For example, according to Scott [1], during the years 1969 and 1970, an average of 47% of the fatal accidents in bituminous coal mines in the USA occurred due to roof falls, falls of face, rib, or pillar, and pressure bumps or bursts. Microseismic techniques should also be applicable during development and production work as a means of continuously monitoring such factors as the quality of roof support systems, the effect of mining rate on the stability of the overall mine structure, and the efficiency of caving operations. Using such techniques, it should be possible to minimize the cost of these operations while insuring maximum safety to mine personnel.

The general scope of this project (Project-MACS) has been the investigation of microseismic techniques relative to coal mine safety. Suitable mobile microseismic monitoring facilities were developed and field studies have been underway in a longwall coal mine in Central Pennsylvania to investigate the feasibility of using microseismic techniques to locate potential zones of instability around coal mine workings. Basically these field studies involve monitoring the microseismic activity generated by a working mine using surface transducers located in shallow boreholes positioned over the active areas of the mine. This study is unique in the fact that measurements are made from the surface rather than underground. This approach provides several advantages, including the fact that there are no electrical limitations on the monitoring system, and that the study in no way interferes with normal mine operations.

In a general sense this project has been a detailed feasibility study in which the practicability of evaluating underground mine stability using surface microseismic monitoring facilities has been investigated. This report describes the study under the following headings:

1. Review of other recent microseismic field studies,
2. Design and development of a mobile microseismic monitoring facility,
3. Evaluation of suitable transducers and transducer installation techniques,
4. Development of data analysis procedures,
5. Selection of a suitable field site, and
6. Preliminary results of microseismic studies at a number of test sites.

The temporal development of the project is outlined briefly in the next chapter.

It should be reiterated at the outset that only <u>preliminary</u> results of the microseismic studies carried out during this project are presented in this report. This is due to the fact that efficient computer based analysis methods were not fully operational when this project [G0101743 (MIN-45)] officially terminated it was considered more efficient to include the refined analysis of these field studies in the final report of a new microseismic project [G0144013] which was initiated October 1, 1973.

PROJECT DEVELOPMENT

When this project was initiated on June 15, 1970, little or no scientific evidence existed to substantiate the fact that microseismic activity generated underground could be successfully detected by surface mounted transducers. The project although highly application oriented, has in actual fact been an extremely fundamental one with all the problems, difficulties, and delays common to such research.

The following is a brief outline of project development during the overall term of the study (June 15, 1970 - March 31, 1974):

1. June 15 - September 15, 1970

   Literature search
   Review of commercially available electronics for monitoring facility
   Initial consideration of microseismic borehole probe design

2. September 16 - December 15, 1970

   Preliminary design of monitoring facility and ordering of major electronic units
   Preliminary consideration of field sites
   Consideration of source location techniques
   Preliminary laboratory studies to determine P- and S-wave velocity in laboratory specimens

3. December 16, 1970 - March 15, 1971

   Design of power supply for monitoring facility
   Consideration of mobility of facility
   Problems encountered in delivery of electronic units for monitoring facility
   Preparation of assembly area for field studies
   Computer studies relative to source location
   Visits to tentative field sites

4. March 16 - June 15, 1971

   Arrival of major electronic units for monitoring facility
   Consideration of van for housing monitoring facilities
   Negotiation with mines for field sites
   Selection of Greenwich field site
   Preliminary laboratory studies on rock from Greenwich mine

5. June 16 - September 15, 1971

Van purchased (non-project funds) and modifications for field use initiated
Trailer unit ordered (non-project funds)
Monitoring facilities under development
Consideration of transducers and transducer installation techniques

6. September 16 - December 15, 1971

Van and trailer modifications completed
Temporary 4-channel version of monitoring facility assembled
Field trials carried out at local sites
Prototype microseismic borehole probe designed and under construction
Rock core obtained from Greenwich mine
Laboratory tests carried out on Greenwich core to obtain elastic, strength and velocity data

7. December 16, 1971 - March 15, 1972

Continued field trials at local sites to debug system
Final 14-channel version of monitoring facility under construction
Prototype borehole probe completed and laboratory evaluation underway
Geological study of Greenwich mine site undertaken
Laboratory studies of Greenwich rock under uniaxial compression undertaken
Preliminary consideration of hybrid computer for analysis of microseismic field data

8. March 16 - July 31, 1972

Completed construction of final version of monitoring facility
Field trials of completed system at a number of local field sites to "debug" system and train personnel
Field trials of prototype microseismic borehole probe at local field site

9. August 1 - November 30, 1972

Detailed evaluation of Greenwich North Mine sites in preparation for preliminary tests
7-geophone shallow burial array installed at Greenwich North Mine air return shaft site
Investigation of background noise problems
New model of borehole probe designed, constructed and tested

10. December 1, 1972 - March 31, 1973

Continued monitoring of geophone array at Greenwich North Mine air return site
Monitoring of activity over A-2 longwall (A-2 site) using surface mounted geophones
Planning of study over B-4 longwall (I(A) site)
Consultation with Electrical Engineering Department, University of Pittsburgh, in regard to data analysis

11. April 1 - June 30, 1973

Monitoring activity over B-4 longwall (I(A) site) with shallow burial geophones
Integration of underground observations and surface activity measurements
Consideration of optimum transducer installation techniques

12. July 1 - September 30, 1973

Continued microseismic monitoring over B-4 longwall (I(A) site)
Deep burial geophone installed over B-4 longwall (I(C) site)
Comparison of data from shallow and deep burial installations
Drilling of deep hole for borehole probe (air return site)
Preliminary tests on borehole probe at air return site
Preliminary development of seismic methods for determination of velocity of strata overlying mine
Initial development of hybrid computer programs for field data analysis

13. October 1, 1973 - March 31, 1974

Continued analysis of field data
Preparation of final project report

REVIEW OF OTHER RECENT MICROSEISMIC FIELD STUDIES

1. Introduction

In the discipline of rock mechanics the major effort relative to the application of microseismic* techniques has been that associated with field studies on geologic structures, i.e. structures composed of, and located in, geologic materials. Unfortunately until recently (Circa 1960) results of such studies have been of limited value. Two recent papers by the writer have presented detailed reviews of recent microseismic research. The first [2] describes in considerable depth the general application of microseismic techniques in rock mechanics (material behavior, model tests and field studies) and includes an extensive literature review (some 90 references) on this subject. The second paper [3] concentrates mainly on microseismic field studies carried out since 1965 and in particular those involved in the evaluation of the stability of geologic field structures. Much of the material presented in this section has been extracted directly from these two papers.

It is important to note that no references have been located which are associated directly with the current coal mine study, although many of the references cited provide useful data on measurement techniques and data analysis procedures which are applicable to the current study.

Historically, microseismic studies associated with geologic materials were initiated in order to evaluate the stability of underground mining operations, and as a method for predicting the occurrence of violent underground

* The terms acoustic emission, rock noise, seismo-acoustic activity, subaudible noise, elastic shocks, and micro-earthquake activity are also utilized by workers in various geologically oriented disciplines such as mining, civil engineering, etc.

disturbances such as rock and coal bursts. During the late 1930's and early 1940's Obert [4,5,6] and Obert and Duvall [7,8,9] showed that in the laboratory as well as in the field, the microseismic rate increased greatly as the specimen or structure became more highly loaded. Conversely, as equilibrium was reached, after a structural failure or a reduction in the applied load, the rate decreased. In other words, the microseismic rate appeared to be a factor indicative of the degree of instability of the structure. With the exception of a few other isolated basic studies the early work of Obert and Duvall has provided the basis for the majority of the geologically oriented microseismic field studies carried out in North America. A recent paper by the author [2] discusses in some detail a number of the early microseismic field studies. In the following section a number of the current applications of microseismic techniques to the evaluation of the stability of geologic structures will be described.

2. Underground Mining Applications

2.1 Hard Rock Mines

In the late 1930's and early 1940's government agencies both in the United States and Canada became involved in microseismic studies related to underground mining. At about the same time similar studies became active in Europe and Asia. These programs were initiated as a result of difficulties experienced in mining at increasing depths or in highly stressed zones; the most spectacular of these being the sudden violent failure of mine structures known as rock bursts [9]. Such studies continued in a relatively routine and uneventful manner until the early 1960's when more sophisticated techniques for monitoring underground microseismic activity were investigated, and in particular techniques for accurate source location were developed. During this period Cook [10] developed a refined monitoring system for use in the

Witwatersrand gold mining area. The system was capable of recording the outputs of up to 16 transducers on magnetic tape for a continuous period of 25 hours. Normally eight transducers were utilized each being connected into two channels of the recording system, the sensitivities of which differed by a factor of 30. In this way events having a wide range of energies could be recorded. As a preliminary investigation had indicated that a large proportion of the microseismic energy in the mining area under study occurred in the frequency range 20-50 Hz the frequency response of the overall monitoring system was restricted to approximately 15-300 Hz. In terms of monitoring facilities developed more recently, such a system would be termed "narrow-band."

In order to determine source locations underground it is necessary to know the velocity of propagation in the associated material. Cook determined this by detonating two or three pounds of explosive at known locations and monitoring the arrival of the resulting stress waves at each of the transducers in his array. Velocities determined in this manner were found to be accurate to within ±5% and it was estimated that the detonation locations could be determined (using the recorded data) to an accuracy of ±10 feet.

The later work of Blake [11,12], Blake and Duvall [13] and Blake and Leighton [14,15] are of particular interest since their monitoring facilities were "wide band" compared to most earlier instrumentation. The system developed by Blake and Leighton [14] was designed to have a flat frequency response in the range of 20 Hz - 10,000 Hz. It is interesting to note these authors state that "the frequencies generated by rock noise contain many high-frequency components." In contrast, Cook [10] indicated that the majority of the events occurred in the frequency range 20-50 Hz. This seeming disagreement is further evidence of our limited appreciation of the overall frequency spectrum involved in microseismic phenomena associated with geologic materials.

Blake and Leighton [14] utilized commercially available piezoelectric accelerometers as microseismic transducers. In use these were cemented to the walls of bore holes drilled in various underground locations. The output of each transducer was connected to a preamplifier located in the bore hole itself, the signal from which was transmitted by cable to a post amplifier and to one channel of a 7-channel FM magnetic tape recorder located at a central monitoring location. Using an array of at least five transducers studies have been carried out in a number of hard rock mines. Data recorded on magnetic tape was processed by re-recording it on a multichannel oscillograph to determine a series of travel time differences. These data along with propagation velocity data obtained in the mine, in a manner similar to that described by Cook earlier, were used to calculate source locations [15]. Blake and Leighton estimated the accuracy of such locations to be within ±10 feet. They concluded that in hard rock mines broad-band monitoring provides much more quantitative information about the behavior of a rock structure than can be obtained using traditional narrow-band facilities. It was their opinion that "when used regularly by experienced personnel, it can become a valuable engineering tool in detecting, delineating and estimating the stability of potential failure zones in rock structures."

Oudenhoven and Tipton [16] describe in a recent paper the results of a Microseismic study conducted in the Climax block cave mine at Climax, Colorado. A planar array of seven accelerometers, located above the block of ore being caved, was utilized to monitor microseismic activity generated during caving. Source locations were determined to an estimated accuracy of ±20 feet.

Although a number of microseismic studies are underway in Europe the majority of these have been associated with coal mines. Exceptions are those in Sweden* and early studies in East Germany [17].

2.2 Coal Mines

To date relatively few microseismic studies have been conducted in North American coal mines partly due to the fact that most active mines are relatively shallow (approximately 500 feet) and hence do not suffer from high stress conditions, and due to experimental difficulties related to the strict laws associated with the use of electrical equipment in such mines. At present however two coal mine oriented projects are in progress supported by the U. S. Bureau of Mines. The first is an in-house project+ underway in a rock burst prone Rocky Mountain coal mine south of Denver, Colorado. Here sections of the mine have been instrumented with velocity sensitive microseismic transducers (geophones). Monitoring facilities, located outside the mine, are similar to those used earlier by Blake and Leighton [14] in hard rock mine studies with the exception that the system is operated narrow-band (90-180 Hz). Results to date have been very encouraging in that it has been possible to define in advance potential zones of instability. The second coal mine project is the subject of this report.

In contrast to most North American coal mines many European coal mines are relatively deep (approximately 2000 feet) and therefore suffer from high stress conditions, and in many cases frequent rock bursts. At present extensive underground microseismic studies are underway in both Poland [18,19,20,21,22,23], Czechoslovakia [24], and Russia [25]. Limited underground microseismic

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* Personal Communication with H. Helfrich, Terratest AB, Bromma, Sweden.

+ Personal Communication with F. Leighton, U. S. Bureau of Mines, Denver, Colorado.

studies are underway in West Germany [26], however an extensive study of coal mine rock bursts in the southern Ruhr Valley (Bochum Area) is presently underway at the Ruhr University+ using surface mounted transducers. Their system when completed will involve a three station array with distances between stations of the order of miles. Each station contains displacement transducers mounted in three orthogonal directions. Transducers, with resonant frequencies of the order of 2 Hz, are utilized and microseismic events are recorded on magnetic tape at each station. Arrangements for a radio or telephone data link between stations is presently under consideration.

3. Surface Mining Applications

In the last few years research in the field of slope stability associated with open pit mining has increased rapidly. Microseismic techniques appear to provide a useful tool for monitoring slope stability, and research by the U. S. Bureau of Mines has contributed a great deal to the development of this technique. The design and installation of microseismic monitoring equipment for slope stability studies presents a number of unique problems which are discussed by Broadbent and Armstrong in a recent paper [27].

Paulsen, Kistler and Thomas [28] have utilized microseismic techniques to study slope stability in an open-pit mine at Boron, California. They sum up the situation by stating that a plot of microseismic activity against time provides a graphic picture of what is going on in the Boron open-pit. An increase in activity over and above the normal background probably indicates that a potential slope stability problem exists. A decrease in activity indicates stabilization may be being achieved, whereas an accelerating activity rate indicates failure may be imminent.

+ Personal Communication with H. Baule and A. Cete, Geophysics Institute, Ruhr University, Bochum, Germany.

During a recent study at Kennecott's Kimbley pit, near Ruth Nevada, extensive microseismic studies were undertaken as part of the routine monitoring of the pit slope stability during slope steepening [29]. In this study microseismic transducers were installed inside two adits driven into the pit wall, as well as in the pit wall itself. Cables from these were connected to a mobile monitoring facility located on surface behind the pit slope. Due to the high ambient noise generated by the mining operation itself measurements were restricted to the times between shifts and on weekends when mining facilities were inactive. During the Kimbley study the pit slope was steepened from about 45° to about 60°. Although the new slope was considered to be a stable one microseismic studies were included in the test program as a safety measure as well as to investigate the correlation, if any, with slope angle. During slope steepening changes in microseismic rate were erratic but appeared to be related to the development of temporary stress concentrations occurring during mining. Following completion of the 60° slope the microseismic rate dropped to a low value indicating the new slope configuration was stable.

4. Petroleum and Natural Gas Applications

Microseismic activity has wide field application in the petroleum and natural gas industry and techniques and results obtained here also have application in mining. The study of hydrofracturing is one application of considerable importance. Here fluids are injected under pressure into low permeability strata with the purpose of fracturing these strata and increasing their permeability and porosity. Such techniques are commonly used to stimulate a poorly producing oil or gas well, or to increase the capacity of an underground gas storage area. Aside from information obtained from surface monitoring of injection pressure and volume, observation well measurements, and examination of rock core drilled after the hydrofracturing, little is really known in regard to the fracturing process that is going on perhaps 5000-10,000 feet below surface. Consideration is being given by a number of workers to the utilization of microseismic techniques to monitor the initiation and propagation of underground fractures associated with hydrofracturing. For example studies presently underway by Overbey and Pasini* are concerned with the development of techniques for determining the location and orientation of underground fractures developed during hydrofracturing.

At present the writer is directing a project [30] which involves the use of microseismic techniques to study the stability of underground gas storage reservoirs (basically zones of porous rock surrounded by impermeable cap rock). This project is supported by the Pipeline Research Committee of the American Gas Association. Additional studies by the writer are also under consideration in which the stability of large cavities located in salt, and commonly utilized for storage of pressurized gases, will be investigated using similar techniques.

5. Civil Engineering Applications

Microseismic techniques appear to be gaining increased attention in civil engineering oriented projects. For example one of the earlier applications of this technique was that of Crandell [31] who employed it as a safety monitor for use in tunneling projects. More recently Beard [32] lists a number of tunneling projects where simple microseismic monitoring devices have been used with great success. Consideration has been given to using the technique for investigating leakage of water reservoirs, and the stability of earth filled dams.+

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* Personal Communication with W. K. Overbey and J. Pasini III, U. S. Bureau of Mines, Morgantown, West Virginia.

+ Personal Communication with R. M. Koerner and A. E. Lord, Drexel University, Philadelphia, Pennsylvania.

Cadman, Goodman and Alstine [33] describe an automated monitoring system for studying landslides. Goodman and Blake [34,35,36] have investigated slope stability associated with potential landslide areas and unstable highway cuts. They determined that there was a definite correlation between the estimated state of slope stability and the observed microseismic rate. They also noted that no microseismic activity was observed in rock cliffs and steep rock cuts subjected to frequent rock falls. According to Goodman and Blake [36] the observed activity in soft landslide materials was found to be in the audio frequency range and appeared to originate within a distance of 100 feet from the microseismic transducer. Furthermore their studies indicated that the source of microseismic events could be located in rockslide areas, but such location was not practical in soft landslide areas, due to the extreme attenuation of high frequency signals and spatial variation of propagation velocity inherent in such materials.

DESIGN AND DEVELOPMENT OF MOBILE MICROSEISMIC MONITORING FACILITY

1. Basic Concepts

One of the main objectives of this project was the design, development and testing of a mobile facility for monitoring microseismic activity associated with operating coal mines. Figure 1 illustrates an example of the basic experimental arrangement utilized - namely an array of transducers positioned over the active mining area, and an associated mobile monitoring facility. In the example shown the activity associated with a longwall operation is being investigated, however the same experimental arrangement is equally applicable to the study of a room and pillar operation, or to development work.

Microseismic activity generated due to development of instabilities in and around the mined areas propagate through the surrounding strata and are detected at the various transducer locations. Figure 2 is a block diagram illustrating a simplified form of a one-channel monitoring system. Microseismic signals detected by the transducer are fed to a preamplifier located near the transducer. The functions of this unit are two-fold; first, to amplify the weak signals generated by the transducer; and secondly, to provide an impedance match to the long cables (100-1000 feet) between the transducer and the main electronic system, located in the monitoring facility. Here the electrical signals are further amplified by a post amplifier unit, passed through a filter (to establish the upper and lower frequency limits of the system), and finally recorded on magnetic tape. Visual recognition of microseismic signals is accomplished by a cathode ray oscilloscope and a UV-recorder.

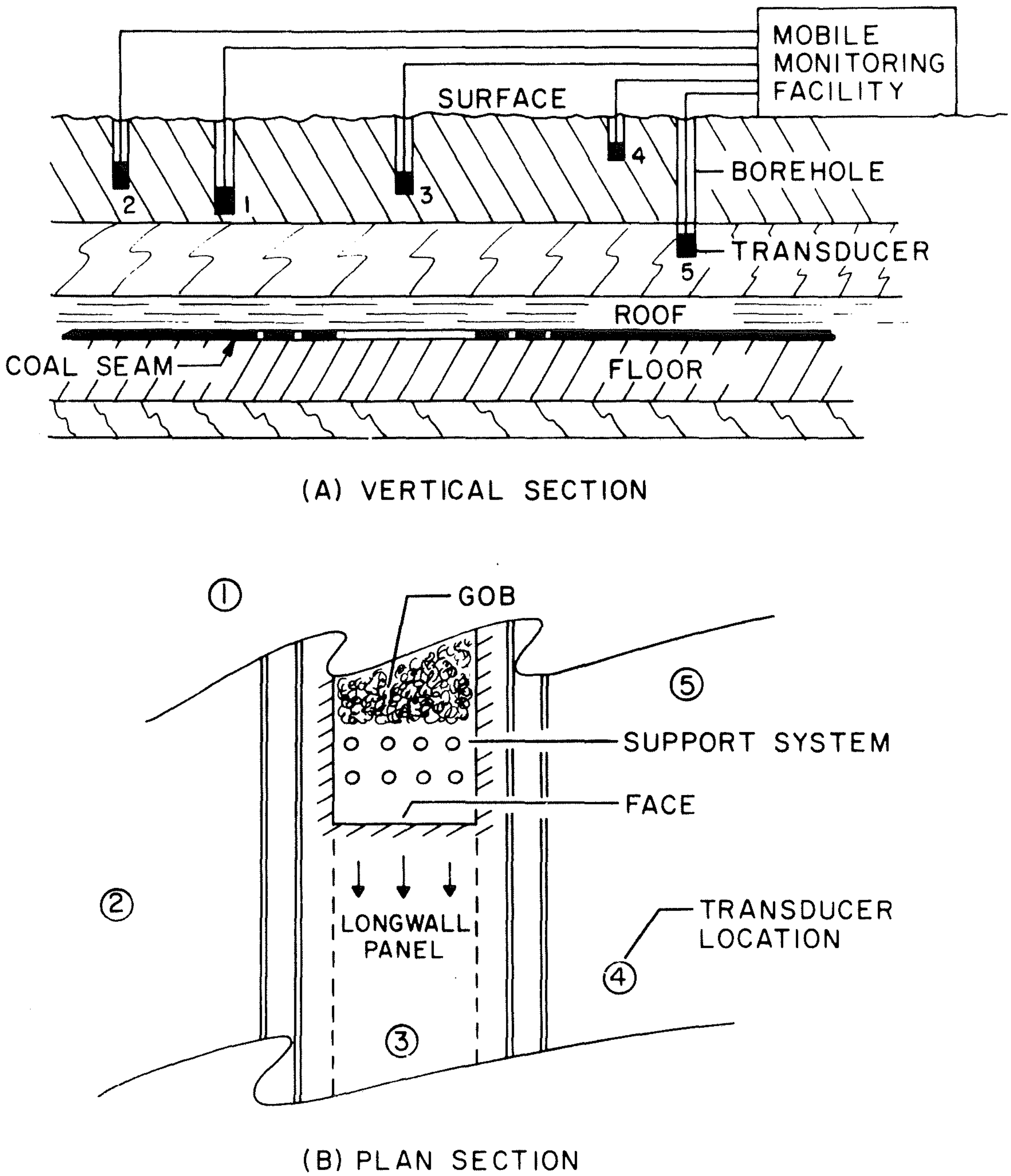

Figure 1 - Basic Experimental Arrangement for Microseismic Study
(Applied here to a longwall operation)

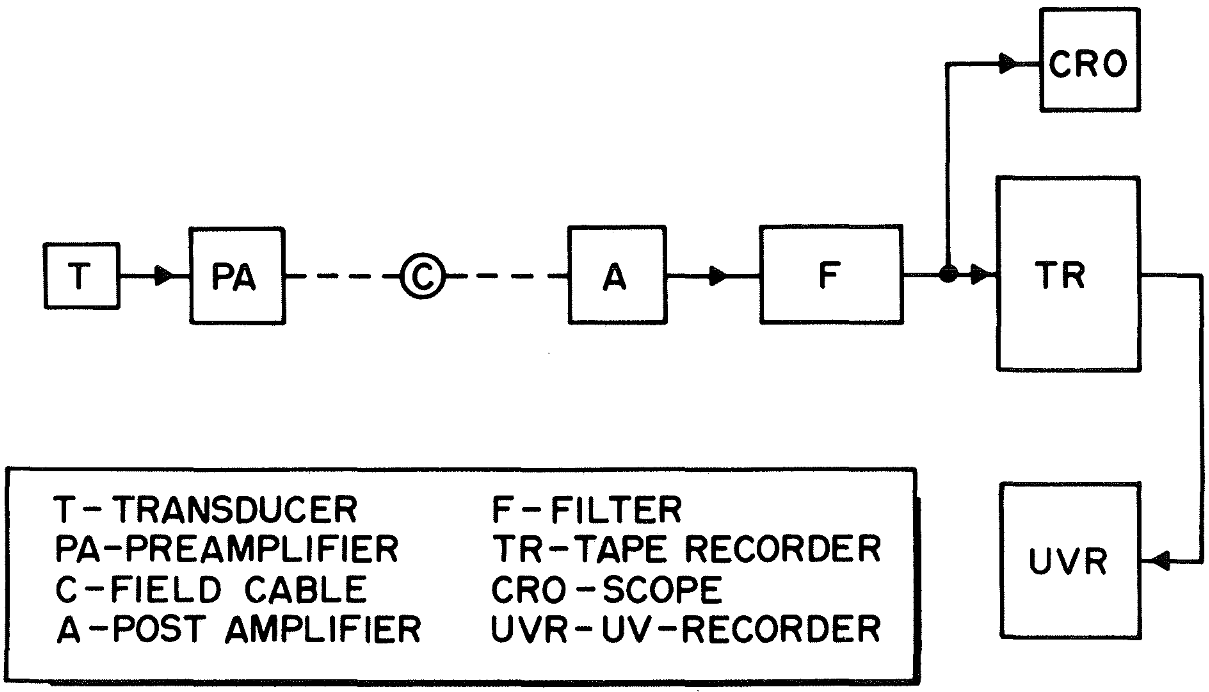

Figure 2 - Block Diagram Illustrating a Simplified Microseismic Monitoring System

Considerable thought was given to the overall design of a suitable monitoring facility. Basic to this design were the following characteristics:

(a) Preliminary function-monitoring
(b) High sensitivity
(c) High signal-to-noise ratio
(d) Broad band frequency response
(e) Electronic configuration flexibility
(f) Above ground utilization
(g) High degree of mobility
(h) Self-contained power

Within the preceding restrictions and the funds and time available a specific system design was developed. By January 1971 the associated electronic equipment was ordered sufficient to assemble a seven-channel system.

The facility was designed basically for data monitoring and recording, although a Honeywell visicorder (UV-recorder) was included for visual display of microseismic data in the field. It was planned that at least initially, however, the majority of the analysis of field data (recorded on magnetic tape) would be carried out in the laboratory.

The overall monitoring system, with the exception of the transducers, was designed to have a broad band frequency response. Although it is appreciated that, in many cases, actual microseismic signals may be of relatively low frequency content (perhaps DC-10 KHz), it was considered advantageous to have the monitoring system as wide band as economically possible.

Since microseismic measurements were to be made using transducers located in surface boreholes, it was necessary that the monitoring facility be located at field sites within a reasonable distance* from all such locations. This necessitated that the facility be designed for operation from its own power source, and it was anticipated that a motor generator and battery power supply would be built into the system for this purpose.

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* At present, this distance is approximately 1200-1500 feet when preamplifier units powered remotely are utilized.

In order to provide the required mobility it was planned to house the overall facility in a small van and attached trailer unit. In this form, at least a primitive road to the test site would be required. Other options such as a heavy duty four-wheel drive truck, semi-permanent trailer facilities, etc. were considered and rejected. A Dodge Van and associated trailer unit were ordered early in 1971 and following delivery were modified for use in this project.

2. Preliminary Monitoring System Configuration

Prior to final design of the monitoring system (basically "packaging", i.e. physical layout, human engineering, interconnection of electronic units, etc.) it was decided to assemble a simplified four-channel system for field testing. In this way the system design could be checked out under field conditions and the necessary modifications made prior to assembly of the final system. Figure 3 shows the components of the preliminary monitoring system. Basically it is similar in form to that shown in Figure 2 with four transducer channels rather than one feeding into the tape recorder. No attempt will be made at this stage to describe the individual electronic units as these are discussed in detail in the next section (Final Design).

During December 1971 and January 1972 field trials of the preliminary microseismic monitoring facilities were carried out locally. Two sites were selected for these studies, namely,

Site A - A road cut located within the borough of State College, and

Site B - An unworked section of a local limestone quarry.

The main purpose of these studies was to study the behavior of monitoring facilities, to investigate the characteristics of a number of different transducer configurations, and to obtain information relative to the frequency-attenuation characteristics of various types of geologic materials. In these

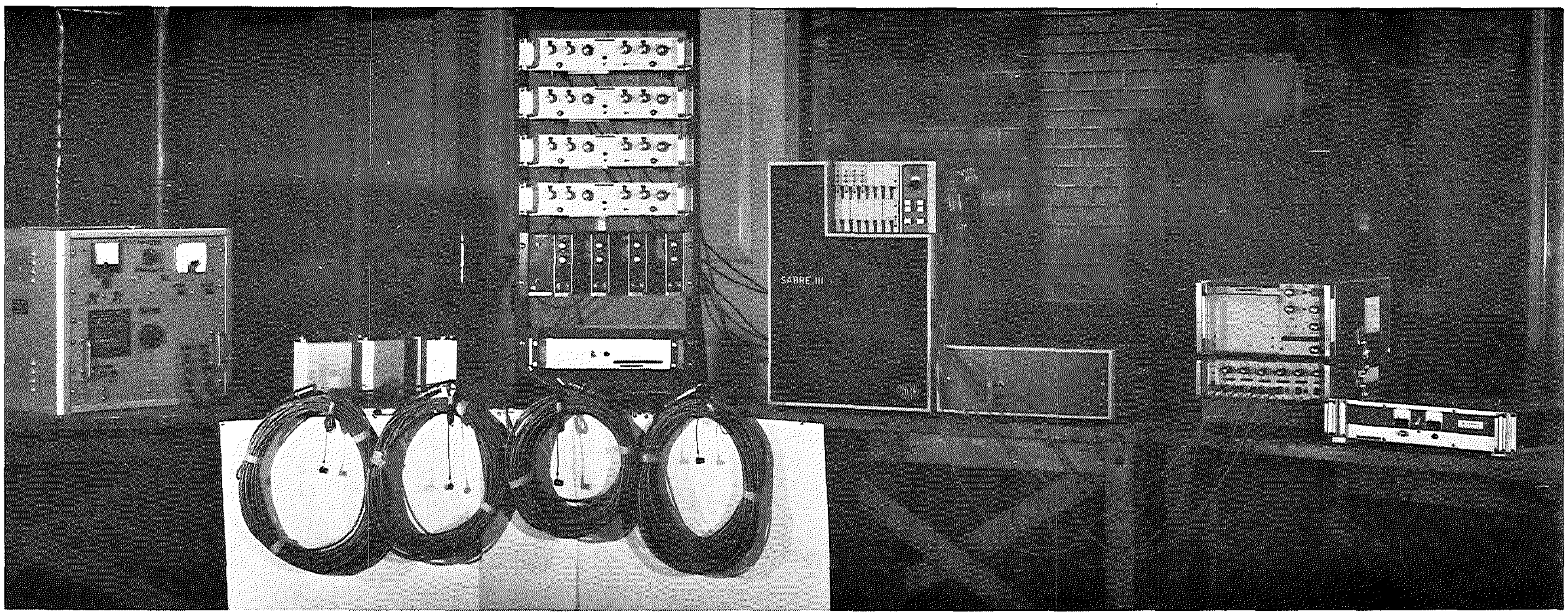


Figure 3 - Preliminary Monitoring System (4-Channel Version)
[From left to right the units are as follows: battery charger, batteries, rack containing filters (top), post amplifiers (center), and inverter (bottom), magnetic tape recorder, tape recorder AC power supply, Visicorder and driver amplifiers and Visicorder AC power supply. A 110 VAC motor generator also used to power the system is not shown]

studies simulated microseismic signals were generated by a sledge hammer, and a Schmit Hammer unit impacting the exposed rock faces.

Details of these field studies are presented in Appendix D. Some of the more important results are as follows:

(1) The Schmit Hammer provides a reproducible and convenient means of applying a low level impact loading to a geologic structure.

(2) Geophones and accelerometers bonded directly to a rock surface are highly sensitive detectors of seismic energy.

(3) An accelerometer is capable of easily detecting Schmit Hammer impact at distances of 50-60 feet.

(4) Using the accelerometer, frequency spectra of seismic signals from a Schmit Hammer at distances of 10-20 feet were in the range of 100-600 Hz. However, components as high as 2400 Hz were observed.

(5) In general all individual units of the monitoring system were found to operate satisfactorily.

(6) Need for the final monitoring system to be solidly mounted and interconnected was quickly apparent.

(7) Need for a multichannel signal patch panel and power supply switching and monitoring facilities in the final system was evident.

Following the preceding field trials the design of the final monitoring system was completed, and a major effort was concentrated on completion of the system. Early in June 1972 the final system was fully assembled and operational.

3. Final Design of Monitoring Facility

It should be pointed out that in a financial sense, the construction of the mobile monitoring facility has been a cooperative venture since the van and trailer unit in which the monitoring facilities are mounted were purchased by the American Gas Association, and the monitoring facilities themselves were purchased from funds provided by the U. S. Bureau of Mines. Through this cooperative arrangement a highly mobile facility has been developed which may be utilized on a number of different field projects, many of which were mutually beneficial. A preliminary report outlining the design of the facility was prepared by Hardy and Kimble [37] in the Fall of 1972; the following is an expanded and updated version of this earlier report.

3.1 Basic Monitoring System

Figure 4 shows a block diagram of the final design of the basic monitoring system in the mobile microseismic facility. The central unit in the system is a 14-channel magnetic tape recorder. On this unit, signals, detected by as many as 14 microseismic transducers, may be simultaneously recorded. The output of each transducer (T) is separately amplified by a preamplifier (PR) and a post-amplifier (A), then passed through a filter (F) before being fed into one of the recorder inputs (RC). Basically, this part of the monitoring system is similar to the simple one-channel system discussed earlier and illustrated in Figure 2, except that there are 14 separate monitoring channels feeding into the tape recorder. Only seven separate filter units are included, but these may be "patched" into any seven active channels. Details and specifications of the amplifiers, filters, and tape recorder are given in Appendix A.

The tape recorder also contains two edge track (ET) channels (one only is shown in Figure 4). These are used to record time, in a coded format, as well as voice during experiments. The time code is generated by a digital clock (DCL) which supplies continuous information on day/hour/minute/second. In order to accurately set the digital clock a standard time [WWV], radio receiver (RA) is also included.

As has been mentioned earlier in this report, the system was designed basically as a monitoring facility; however, in order to examine the general quality of recorded data in the field, a multi-channel UV-recorder (Visicorder) was included along with a set of driver amplifiers (D). The latter are

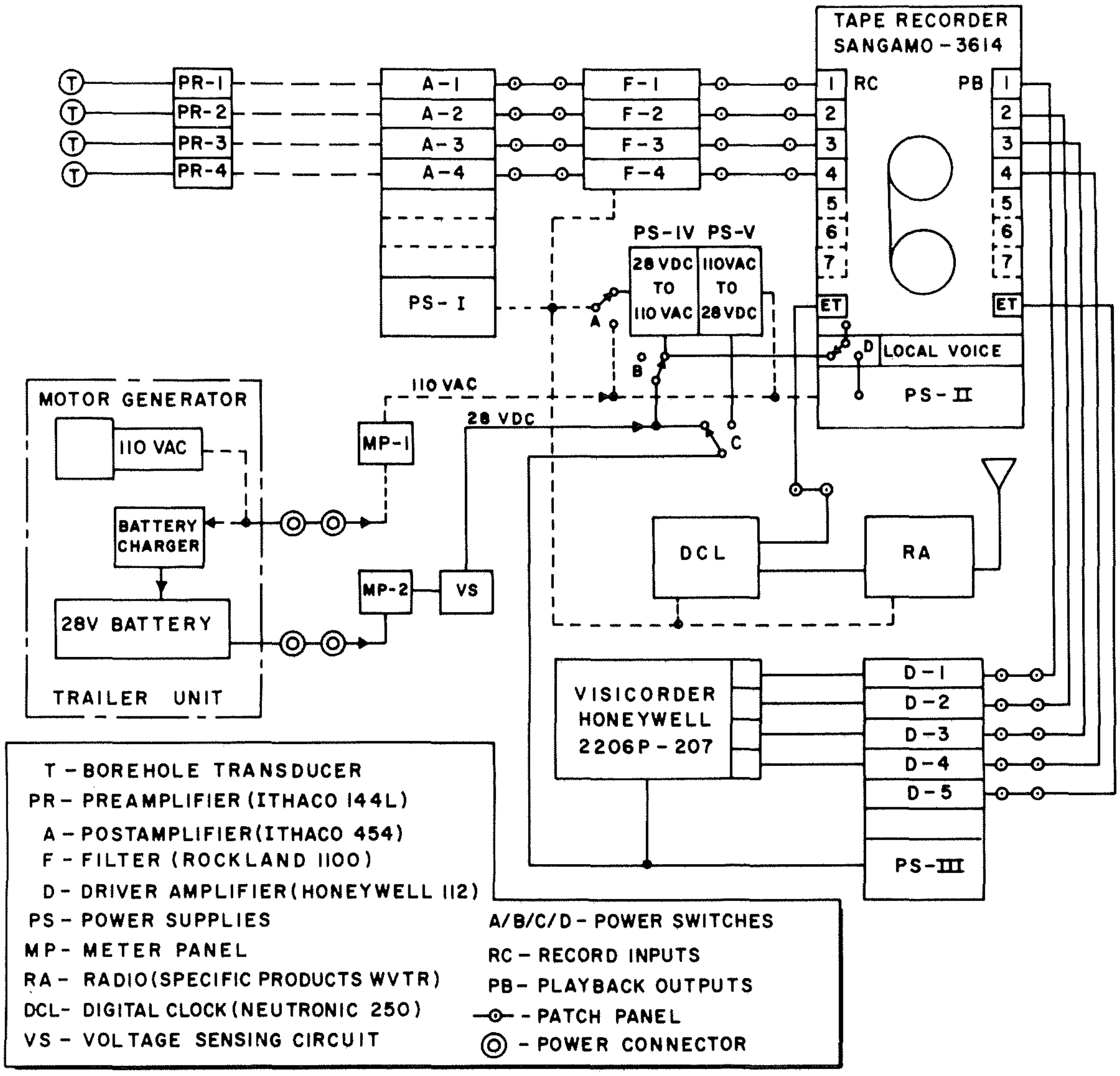


Figure 4 - Block Diagram of the Basic Monitoring System in the Mobile Microseismic Facility

necessary to boost the recorder output signals (PB) sufficiently to operate the UV-recorder. Specifications for the UV-recorder and associated amplifiers as well as the digital clock and standard radio mentioned earlier are given in Appendix A.

Figure 5 shows a front view of the basic monitoring system. For convenience, it was mounted in a specially designed rack unit. Also included are a series of power supplies (PS-I, II, III & V), metering and switching circuits (MP-1,-2), a voltage sensing circuit (VS) for control of power to the various electronic units, and a signal patch panel. Particular care was taken in mounting and inter-wiring of the various units to insure long-term stability and reliability of the overall system. Signal and power cables were well separated, and all cables were securely "tied down" to the rack frame. Figure 6 shows a rear view of the basic monitoring system which shows some of the wiring.

Power for the monitoring system may be provided from batteries in the trailer unit or from 110 VAC supplied by a motor generator or local power lines. A more detailed description of the power system will be presented later in this report. It should be noted at this point, however, that switching and monitoring circuits are located in the rack which allow local selection of AC or DC power for operation of the associated electronics (i.e., amplifiers, filters, tape recorder, etc.). A simplified block diagram of the power system is included in Figure 4. Metering of AC and DC power is accomplished by MP-1 and MP-2 respectively. Switches A, B, C, and D allow AC or DC power to be selected for the various units. Also included is a voltage sensing circuit (VS) which insures that the DC supply is shut off when the battery voltage drops below a critical level. This is necessary to protect the Silvercell batteries from damage. The circuit of the voltage sensing circuit is given

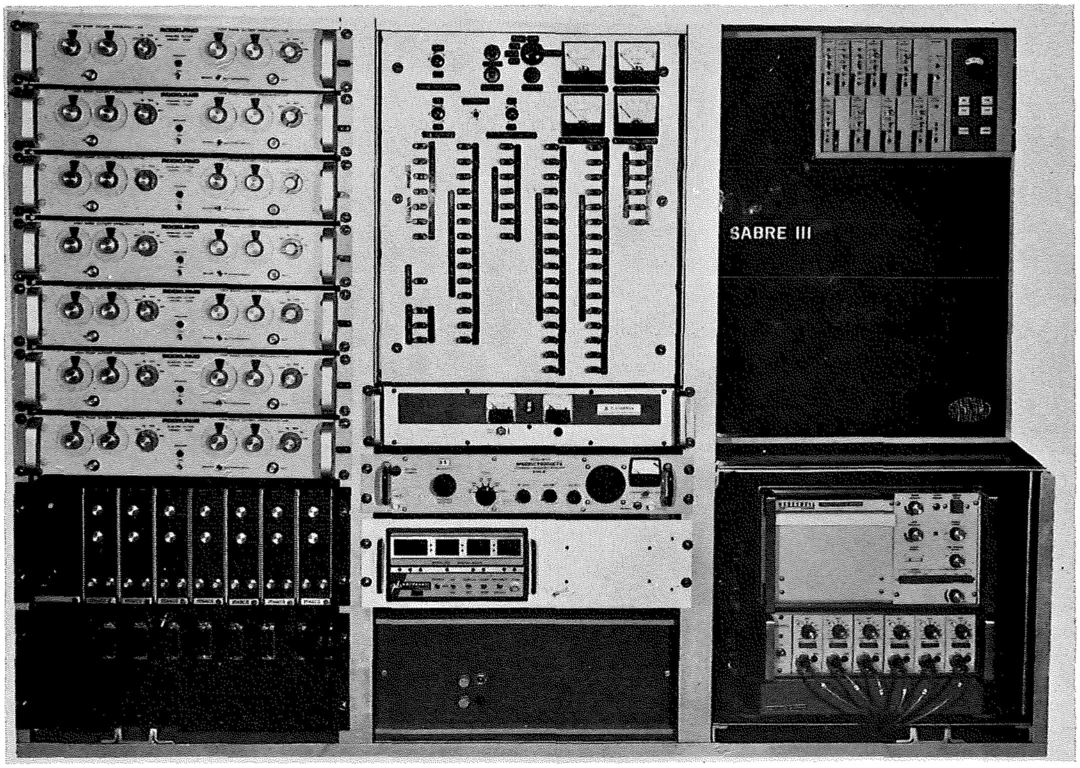


Figure 5 - Front View of Basic Monitoring System in Microseismic Monitoring Facility [The left rack contains at top, seven filter units, and at bottom, two sets of post amplifiers. The middle rack contains at top, the power switching and monitoring facilities and the signal patch panel; below this is power supply PS-V, the radio, digital clock and power supply PS-II. The right rack contains at the top, the tape recorder; and below, the UV-recorder and driver amplifiers]

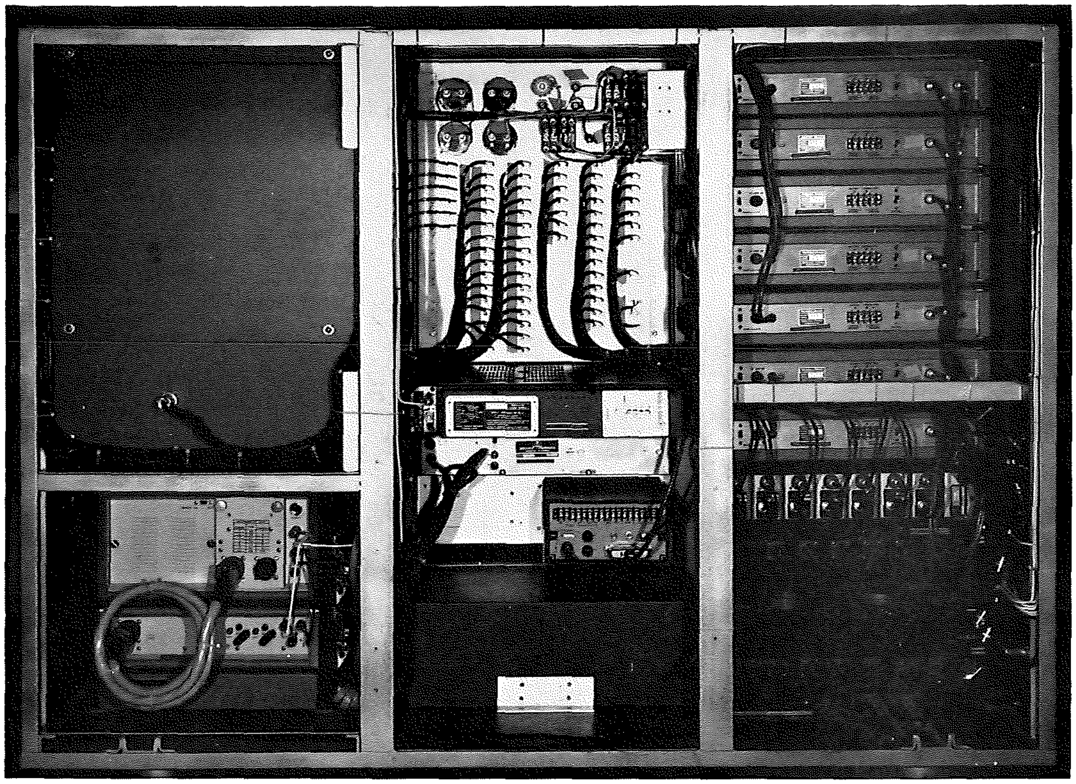
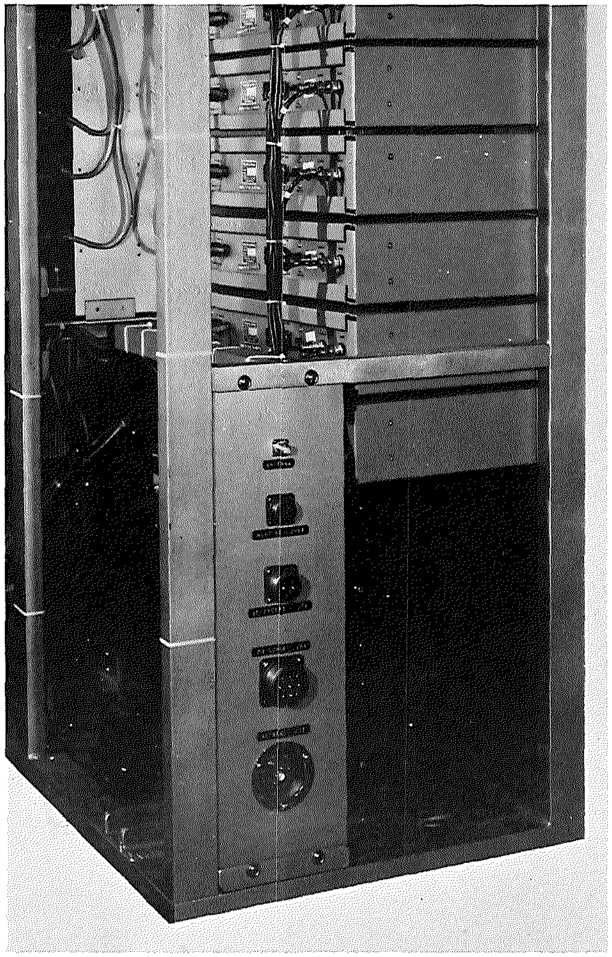


Figure 6 - Rear View of Basic Monitoring System
[At the left top is the tape recorder with the UV-recorder and driver amplifiers below. In the middle top is the power switching and monitoring facilities, and the signal patch panel. Below is power supply PS-V, the radio, digital clock and power supply PS-II. At the right top are the seven filter units and below, the two sets of post amplifiers]

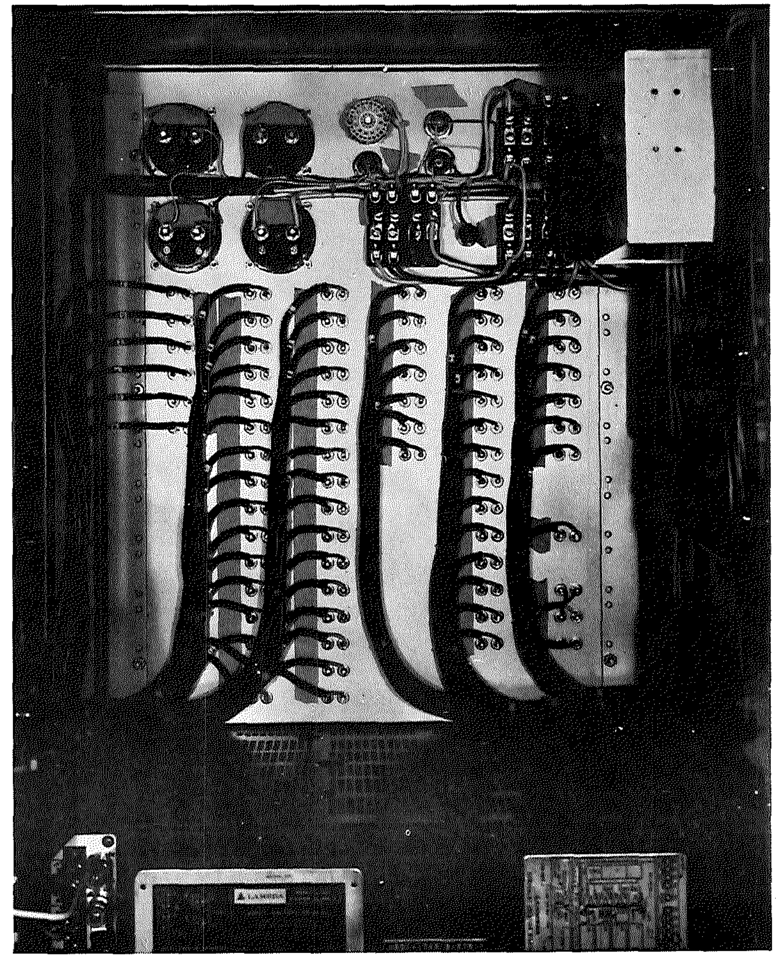
in Appendix B. AC and DC power connections to the equipment rack are made through a series of connectors mounted on the side of the rack as shown in Figure 7A. The upper section of the panel, shown in Figure 7B, contains the power switching and monitoring circuits.

To provide as flexible a monitoring system as possible, the input and output connections of many of the electronic units in the monitoring system have been terminated at a signal patch panel (see Figures 5 and 6). A number of the patch panel connections have been shown diagramatically in Figure 4. This patch panel arrangement allows plug-in connection to the following: post amplifier outputs, filter inputs and outputs, tape recorder inputs and outputs, and UV-recorder inputs. As well, connections to a series of three monitor lines and the output of the digital clock are also included. A more detailed outline of the patch panel arrangement is shown in Figure 8, and a rear view of the wired panel is shown in Figure 7B. Besides making it extremely convenient to arrange the composition of each separate signal channel, the patch panel also provides convenient test points throughout each channel for insertion and monitoring of test signals (e.g., during calibration and "trouble shooting").

The rack unit in which the basic monitoring system is mounted was designed specifically to hold the necessary electronic equipment and to fit conveniently into a Dodge van for transport. The rack itself is mounted to a large aluminum base by a series of vibration isolating mounts. When in position within the van, the base plate itself is bolted, through a series of threaded mounting plates, directly to the van frame. Figure 9 shows two additional views of the completed system prior to mounting in the van.



(A) Power and Other Connectors on Side of Equipment Rack [Top two connectors are for radio antenna and signal monitor lines. Bottom three connectors are for power]



(B) Rear of Power Switching and Monitoring, and Signal Patch Panels

Figure 7 - Details of Power and Patch Board Circuits

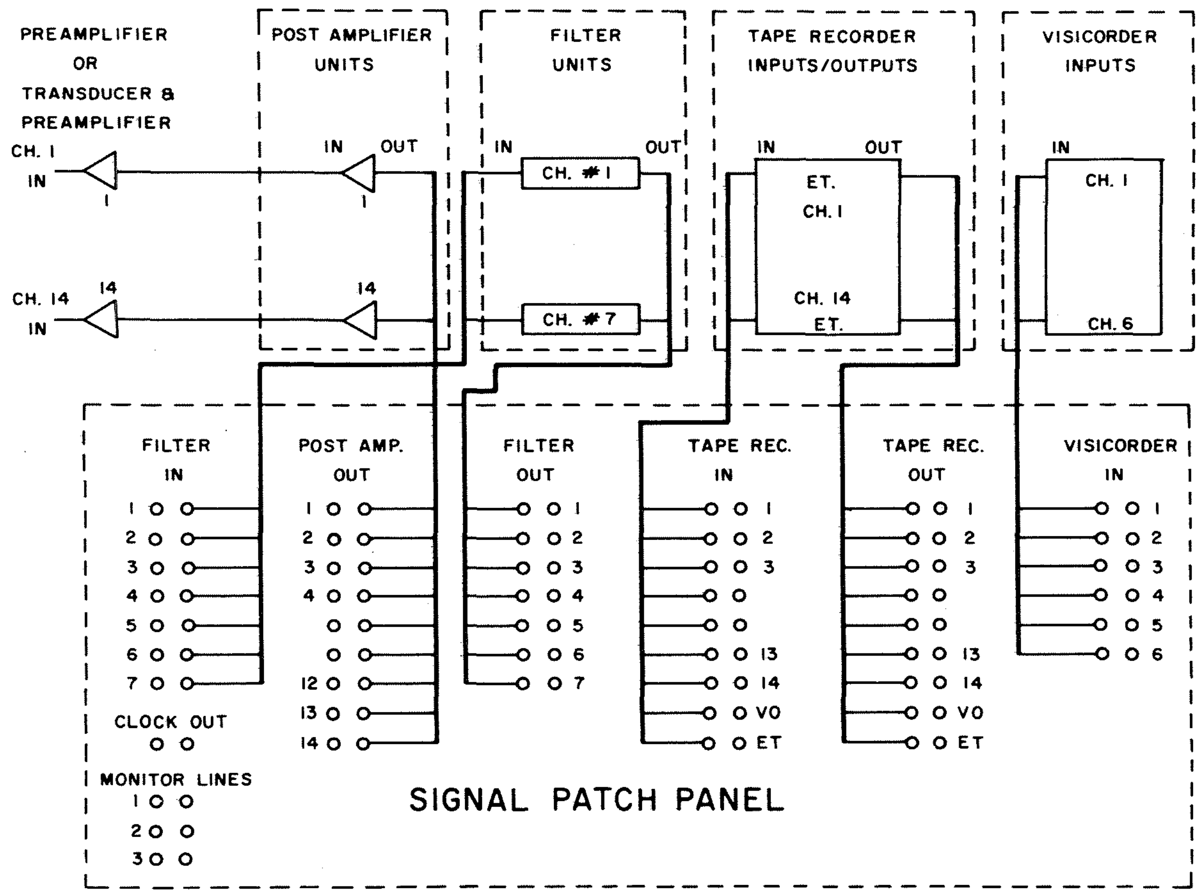
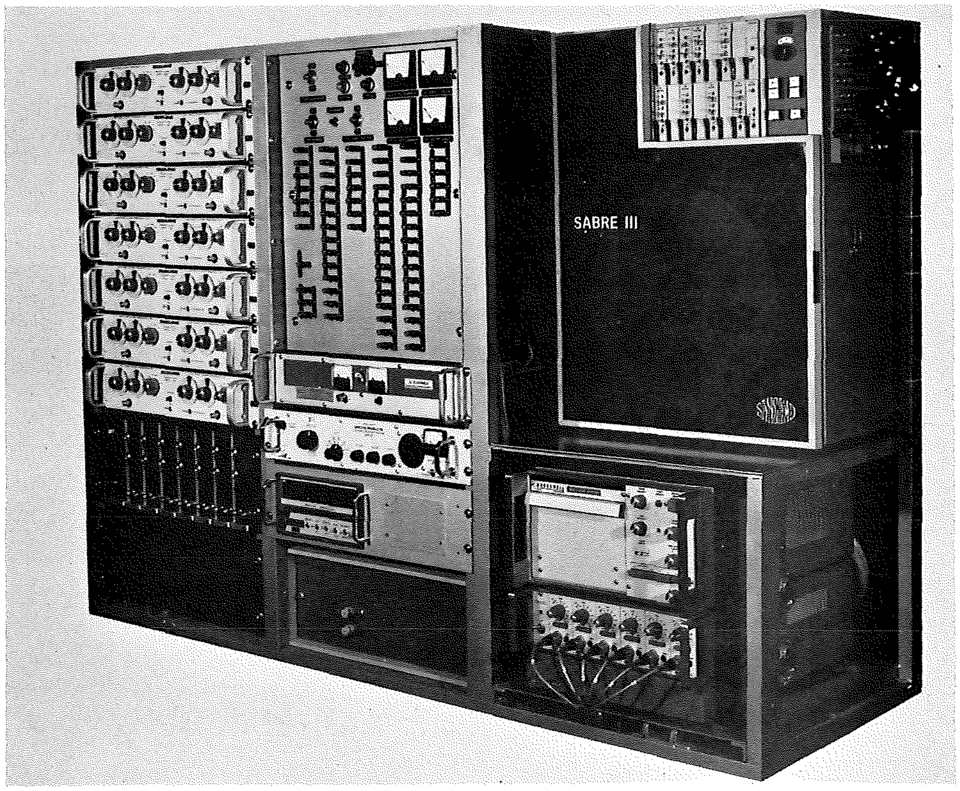
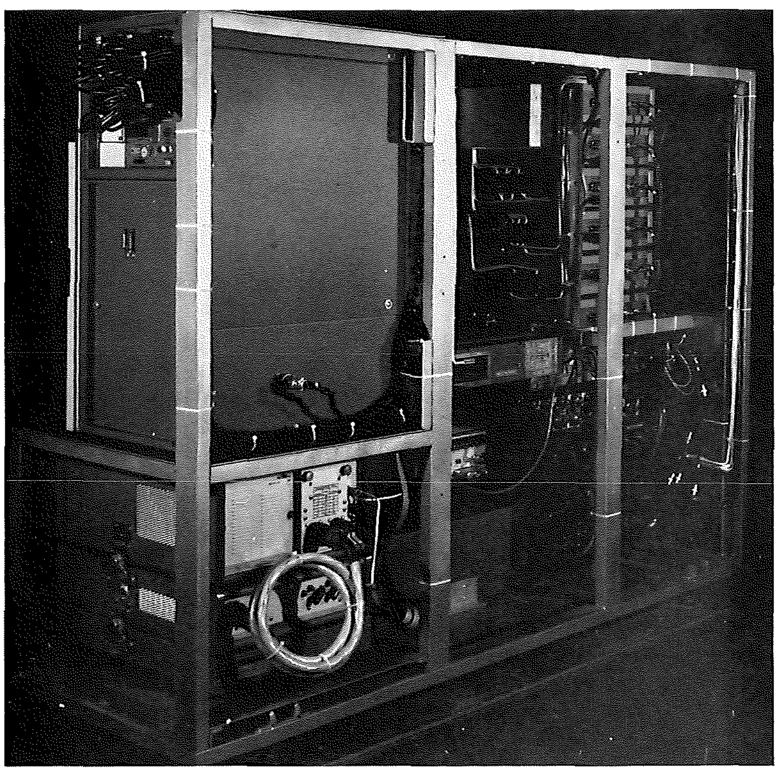


Figure 8 - Block Diagram of Patch Panel Circuits



(A) Front View of Monitoring System



(B) Rear View of Monitoring System

Figure 9 - Front and Rear Views of Monitoring System Prior to Mounting in Van

3.2 Modification and Outfitting of Van and Trailer

Van Details - Early in the development of the microseismic monitoring facility, it was appreciated that for greatest flexibility the overall system should be as portable as possible. The weight and complexity of the required system immediately eliminated the possibility of hand portability, and it was decided to install the system in a motor vehicle. A Dodge B-300 series van was considered to be the best suited for the purpose. Figure 10 shows the van soon after purchase and prior to the necessary outfitting and modification. Figure 11 shows an interior view of the modified van, with the monitoring system rack removed.

Important modifications included the following:

(1) Installation of a 3/4-inch thick plywood floor over the existing metal floor to provide additional strength.

(2) Installation of a roof-mounted air conditioning system for operation from 110 VAC when the van is in a stationary location.

(3) Installation of a screened adjustable roof vent.

(4) Insulation of the walls and ceiling of the van with one-inch thick styrofoam cemented in position using Scotch Weld Structural Adhesive.

(5) Installation of a complete AC and DC input panel and distribution system.

(6) Construction and installation of a combined work bench-storage area, and a storage cabinet for a two-way radio system.

(7) Installation of a fixed roof antenna for the base two-way radio unit.

(8) Installation of two transducer cable ports through left side of van near monitoring rack (see Figure 15).

Figure 12 shows a view of the work bench-storage area. The frame of the unit was constructed of angle iron and welded into a one piece unit. In position, it is bolted to the walls and floor of the van. Two drawers and a lower cupboard area were provided for storage of cables, electronic components,

Figure 10 - Dodge B-300 Series Van Prior to Outfitting and Modification

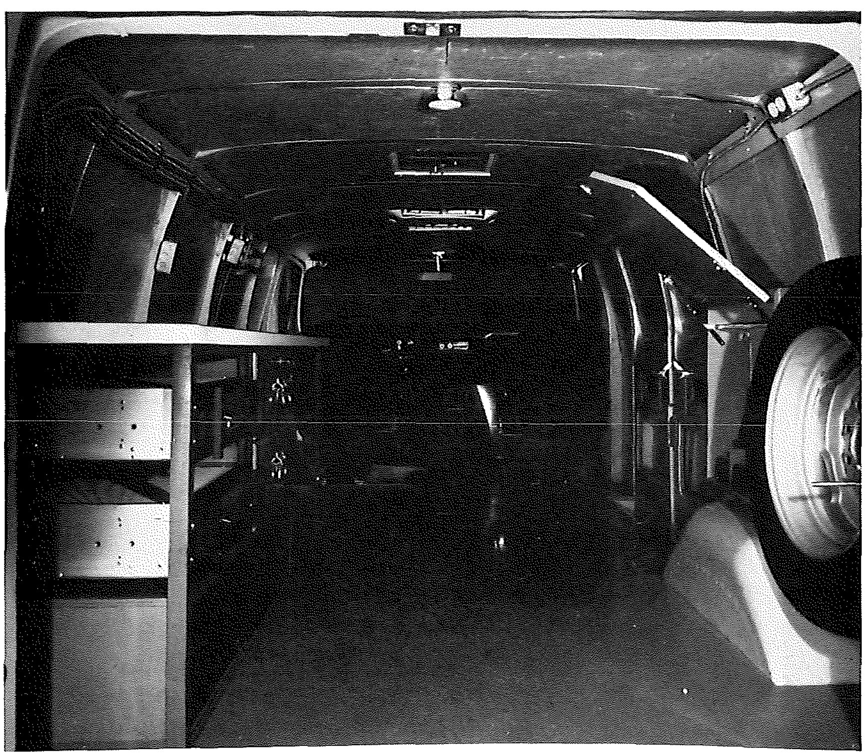


Figure 11 - Interior of Modified Van With Monitoring System Rack Removed

tools, etc. The top left-hand area of the bench was designed as an open rack for mounting two DC-AC inverters. To the left in the area above the bench can be seen the AC and DC power input panels.

The storage cabinet for the two-way radio units is shown in Figure 13. Space was provided for storage of the radios and their associated battery chargers, as well as associated leather carrying cases and straps. A duplex 110 VAC outlet was installed inside the cabinet to supply power to the battery charger units. The cabinet was supplied with a keyed lock for security purposes. Appendix A lists the specifications for the two-way radios.

AC and DC power to the monitoring system enters the van on the left-rear side by way of a series of heavy duty connectors. These are wired directly to a series of circuit breakers mounted in input panels on the inner wall of the van (see Figure 12). From this location, AC and DC lines are wired (using armoured cable) to an intermediate power panel, shown in Figure 15, near the monitoring system rack. Flexible cables connect the rack to the intermediate power panel. A number of 110 VAC lines are also wired into duplex outlets at various locations inside the van, as well as to a connector on the left-rear of the van which supplies 110 VAC power to the trailer unit housing the DC battery supply. Also included in the power supply system are two DC-AC inverters, see Figure 16, which provide 110 VAC power, from the storage battery supply, for operation of the filters, post amplifiers, WWV radio, and digital clock. The other electronic equipment may be operated directly from the battery supply. Appendix A lists the inverter specifications. The overall details of the power supply system are given in a series of circuits presented in Appendix B (Figures B-2 to B-5).

Figure 17 shows a front and rear view of the monitoring system in position within the van following completion of the van modification. The

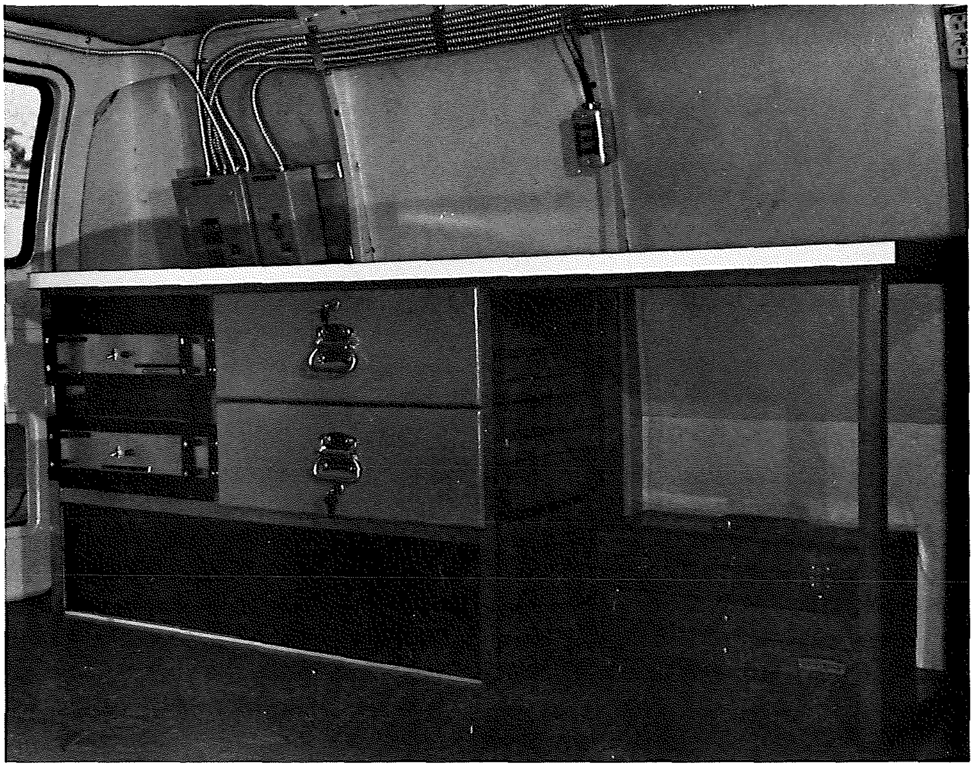


Figure 12 - Work Bench-Storage Area

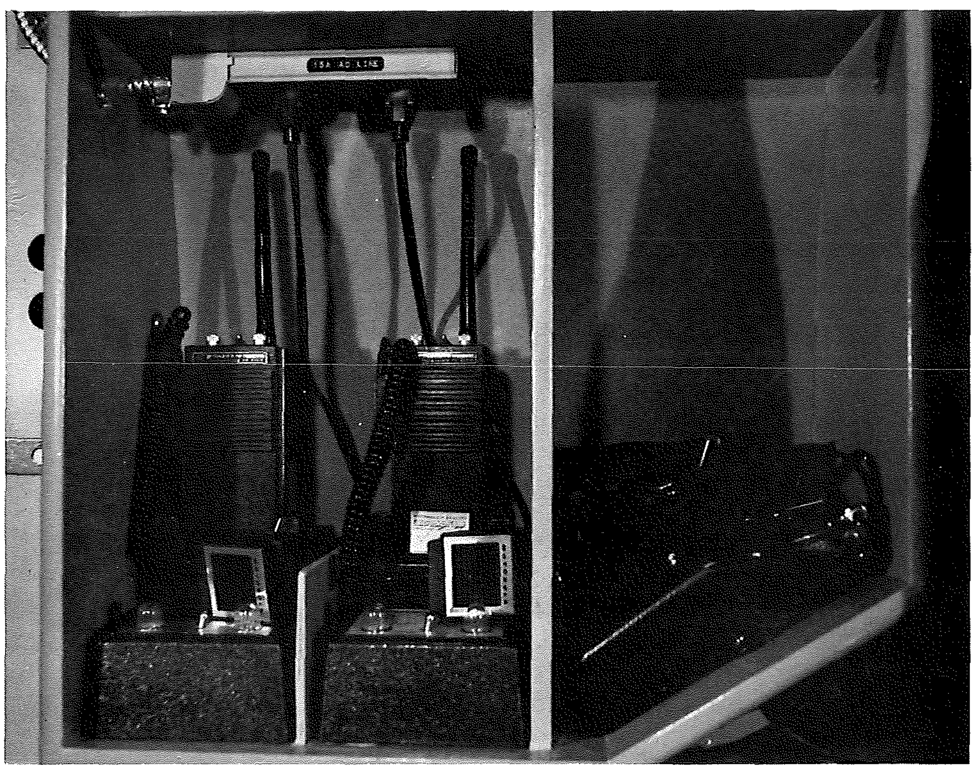


Figure 13 - Two-Way Radio Storage Cabinet

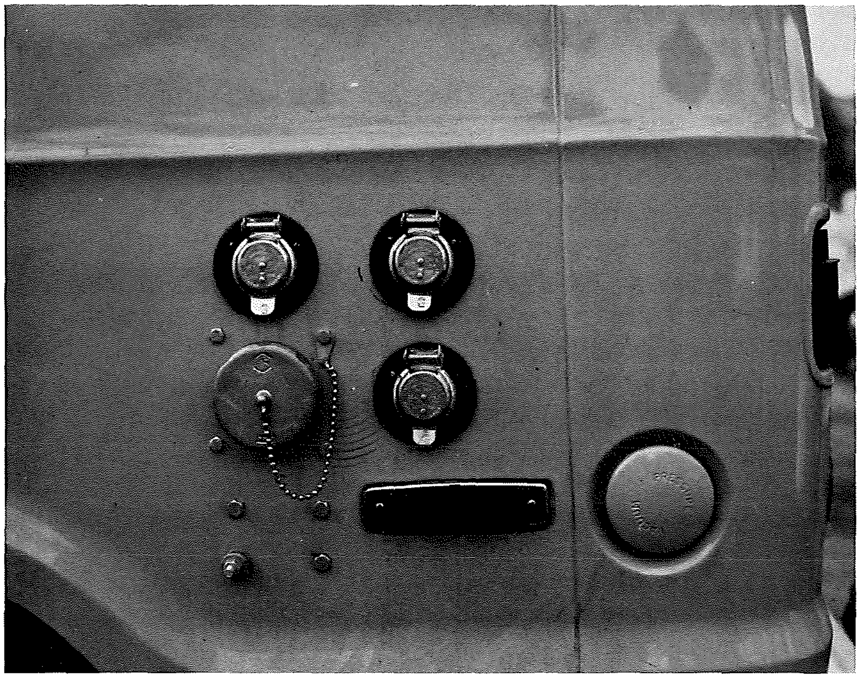


Figure 14 - AC and DC Power Connections at Rear of Van

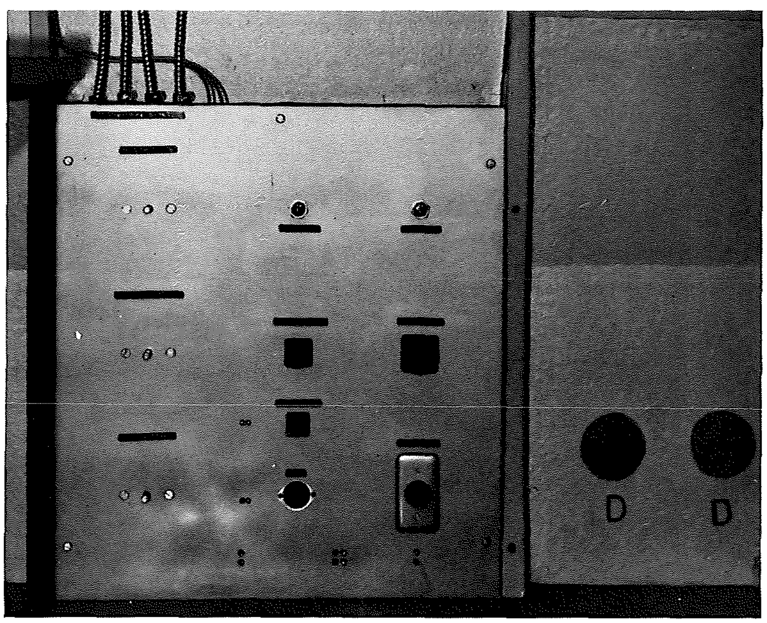


Figure 15 - Intermediate Power Panel on Inner Wall of Van Near Monitoring System Rack [The two holes (D) at the bottom right hand side are transducer cable ducts through the wall of the van]

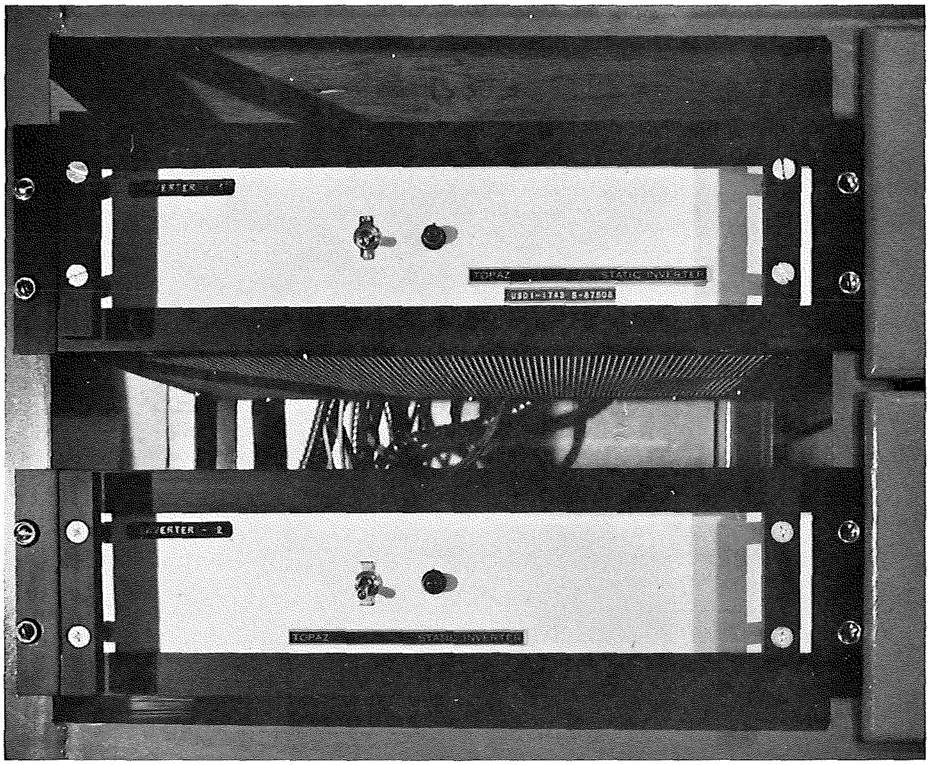
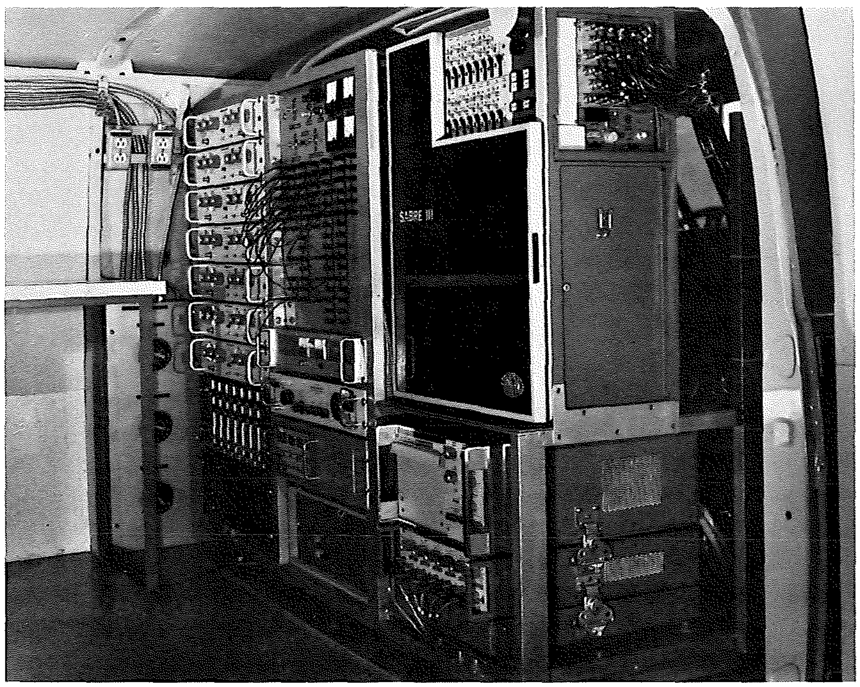
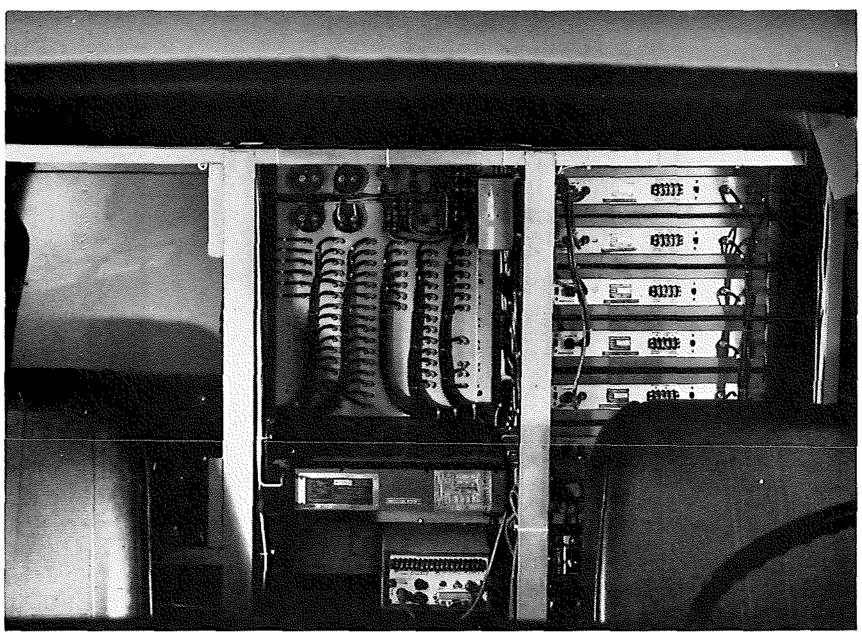


Figure 16 - DC-AC Inverter Units



(A) View from Rear of Van



(B) View from Front Seat of Van

Figure 17 - Two Views of the Monitoring System in Position in the Modified Van

installation is such that all sections of the instrumentation are easily accessible from the front and rear of the rack. For servicing or laboratory use, the complete rack is easily removed from the van onto a heavy duty cart.

Trailer Details - In order to provide space for the DC battery supply, the AC motor generator, and supplies and tools, a small trailer unit was purchased. Specifications are given in Appendix A. During field trips, the trailer is hitched to the van and hauled to the field site. In this way, the complete monitoring facility may be easily transported and set up by two persons. Figure 18 shows an inside view of the trailer unit with the various packing cases (used to store tools, electrical cable, transducers, etc.) removed. A heavy duty shelf was constructed at the front of the trailer for mounting of the battery charger and two battery packs. The motor generator is stored on the floor below the shelf and is provided with a mechanical clamping arrangement for securing it during transport. Appendix A lists the important specifications of the batteries, charger, and motor generator. A close-up view of the motor generator is shown in Figure 19.

All wiring between the battery charger and the two battery packs was permanently installed in the trailer. A switching unit for selection of "on-line batteries" and "battery under charge" was installed on the trailer wall above and behind the battery charger (see top-center, Figure 18). The circuit for the switching unit is given in Appendix B (Figure B-6).

4. Operating Characteristics - Field Trials

The mobile microseismic monitoring facility, as shown in Figure 20, was completed early in the Summer of 1972. During August and September, a series of "shake-down" trials were conducted at various field sites. A number of difficulties were encountered, mainly associated with the AC and DC power

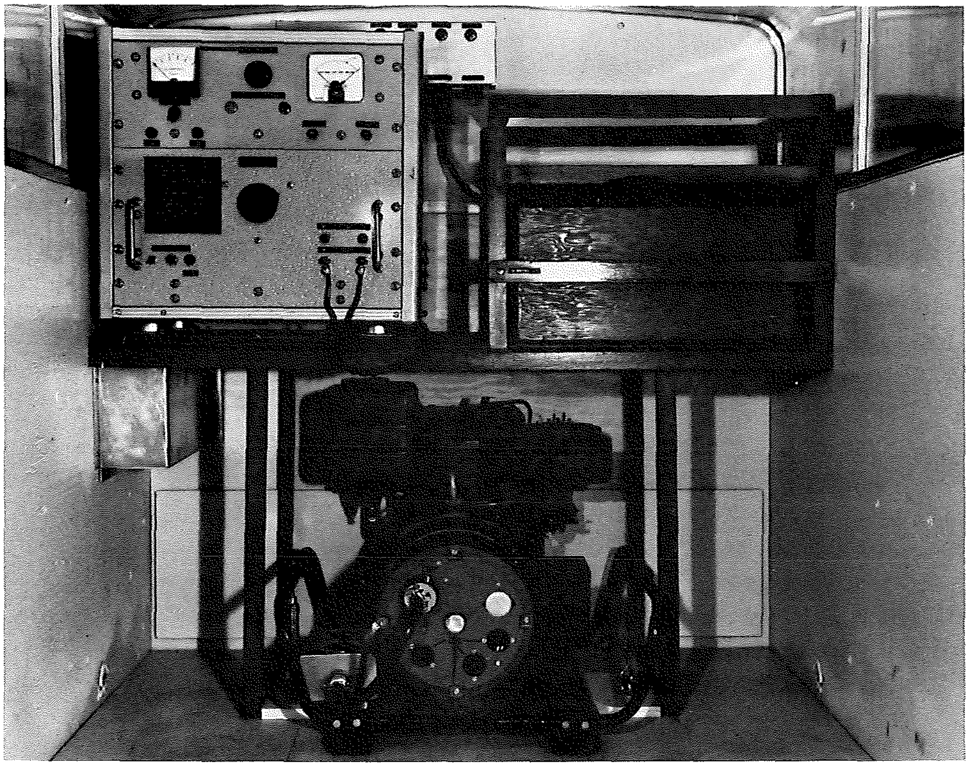


Figure 18 - Inside View of Trailer Unit
[Left top - battery charger, Right top - batteries,
Lower center - motor generator unit]

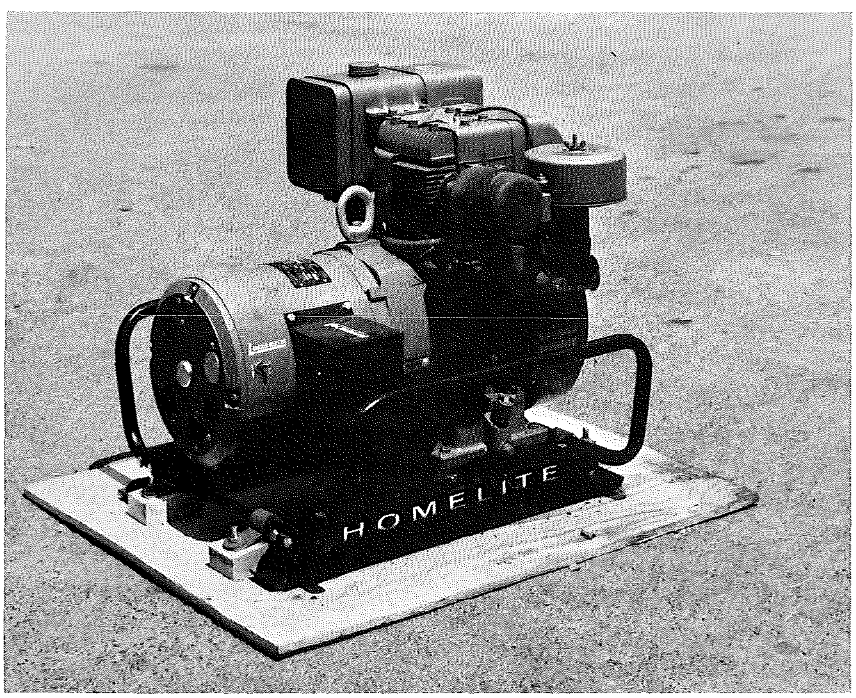


Figure 19 - Close-Up View of Motor Generator

Figure 20 - View of Completed Mobile Microseismic Monitoring
Facility Ready for Field Use

systems. The majority of these have been rectified, although at high system gains some difficulties due to "noise spikes" on the 110 VAC power from the generator and the inverter units are still not fully resolved. In general however the overall monitoring facility has fulfilled the design requirements listed earlier. During field trials it was possible to drive to a test site, set up the system, connect into pre-installed transducers, and be fully operational within one hour after arrival. There is no doubt therefore that the cost, time, and effort expended in design and construction of the facility will pay great dividends in future field studies.

Experience gained during the development of the mobile microseismic monitoring facility had indicated that the most critical problem was that of developing a system with a high signal-to-noise ratio. This can only be accomplished by the following:

(1) Use of electronic equipment and components with the lowest available noise figures,

(2) Interconnection of equipment in the most stable manner (electrical and physical) possible, and

(3) Careful design of the overall grounding system.

Items 1 and 2 are factors which one normally considers, at least to some degree, when developing an instrument package for a specific study. In the current project however extra care in selection of the lowest noise equipment and components, and in construction of the system was of prime importance.

Unfortunately however unless even greater consideration is given to item 3, system grounding, it will not be possible to develop a system with a suitably high signal-to-noise ratio. To some extent optimum methods of grounding in low-level signal systems are somewhat of an art, although a number of texts have become available on the subject (e.g. the recent book by Morrison [38]). Figure 21 shows a simplified block diagram of the signal and ground system involved in the microseismic monitoring facility. Where possible signal commons have been kept free of the equipment case grounds. This has been possible for most units in the signal line (preamplifiers, post amplifiers and filters) although it was not possible for the tape recorder. As shown in Figure 21 all signal common lines were terminated at a single point (1). Similarly the cases of all instruments were connected to the equipment rack which itself was connected to the van chassis/van power ground. The frame of the motor generator was also tied to this ground system. A single jumper joins the signal common to the rack ground (points 1 & 2, Figure 21). An external earth ground may be connected to the van chassis/van power ground system at point 3.

A specific value for the noise level of the overall monitoring system (including transducers) is extremely difficult to determine since it depends on the test location, and environmental conditions on the test day. A series of experiments were however carried out to evaluate the inherent noise in the electronic system itself (excluding effects due to the transducer, and the motor generator). These tests were carried out while the monitoring facility was located inside a building and operating from 110 VAC building power.

To measure the intrinsic noise in the microseismic monitoring facility the input of the preamplifiers of two channels were shunted with 910 ohm resistors, to simulate the geophone impedance, and recordings were made. The magnetic tape was then played back through the UV-recorder and the signals were calibrated against a one volt test signal.

For a pass-band of 10 to 250 Hz and the system set at a total gain of 126 decibels (approximate voltage ratio of 2×10^6), the average peak-to-peak noise signal for the two channels was 1.7 inches on the UV-recorder. This is equivalent to an output signal of 1.1 volts peak to peak.

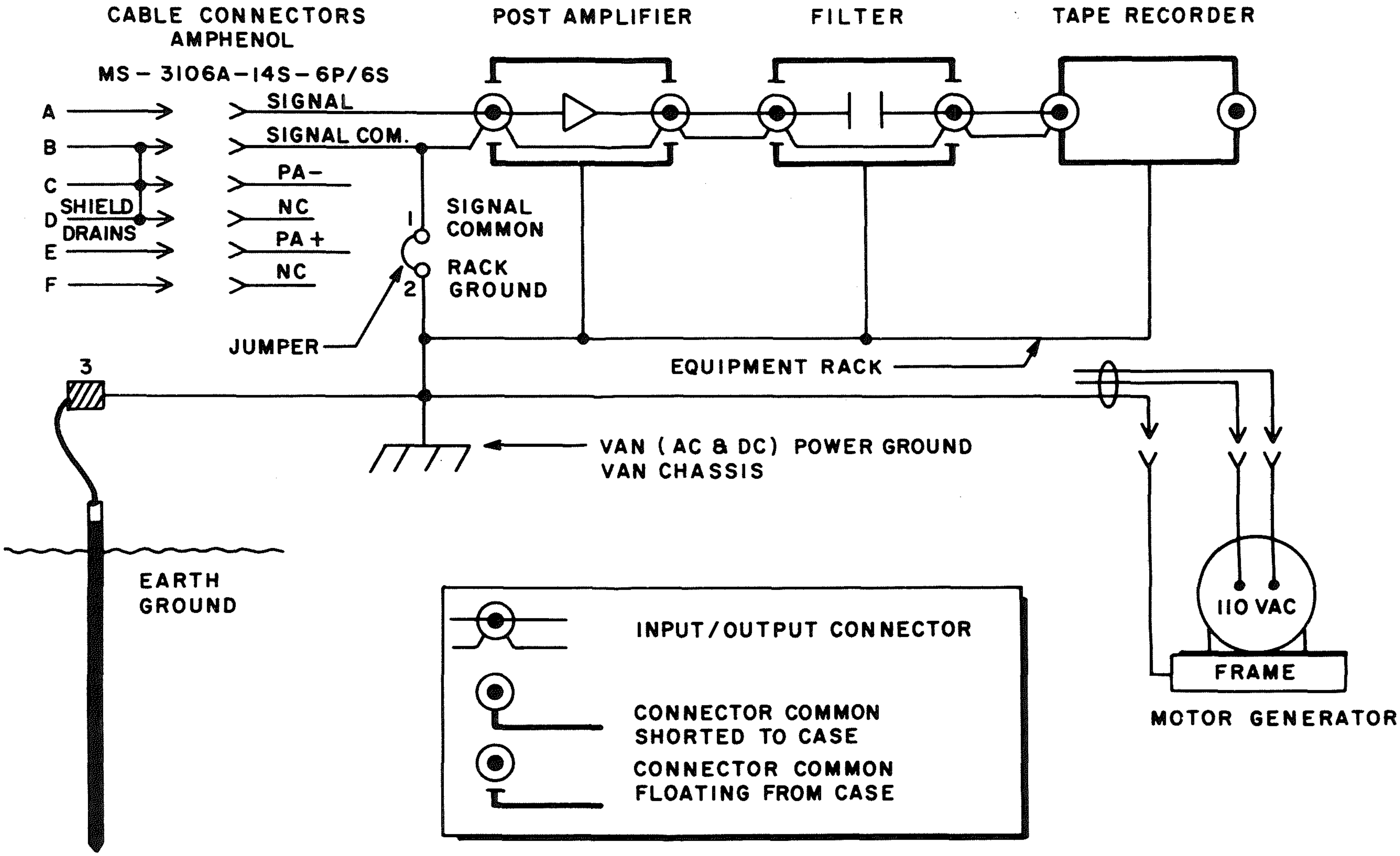


Figure 21 - Simplified Block Diagram of Signal and Ground System in Microseismic Monitoring Facility

Now $$\frac{\text{output}}{\text{input}} = \text{voltage ratio}$$

and $$\frac{1.1}{\text{Input}} = 2\text{x}10^6$$

therefore $$\text{Noise Input} = 5.5\text{x}10^{-7} \text{ volts peak-to-peak}$$

or $$\text{Noise Input} = 1.4\text{x}10^{-7} \text{ volts RMS.}$$

For a bandpass of 10-250 Hz we divide by $\sqrt{240}$ to get

$$\eta_e = 8.9 \times 10^{-9} \text{ volts RMS}/\sqrt{\text{Hz}}$$

Over the whole pass-band the response of the geophones normally utilized in field studies is approximately 0.6 volts/in/sec. Therefore the equivalent RMS ground motion will be

$$\eta_g = \eta_e/0.6$$

$$\eta_g = 1.5\text{x}10^{-8} \text{ in/sec}/\sqrt{\text{Hz}}.$$

This intrinsic noise figure is considered to be excellent for the types of studies planned with the facility.

It must be pointed out however that the above figure was obtained under optimum conditions. In actual field situations a figure somewhat higher would be expected for the overall monitoring system since noise from the motor generator, and from ambient effects on the geophone itself would be superimposed on the intrinsic system noise.

TRANSDUCERS AND TRANSDUCER INSTALLATION

1. Introduction

When a structure is loaded stress waves are generated due to localized deformation and/or failure at areas of high stress concentration. Microseismic activity at a specific point in the structure may be detected by monitoring the displacements, velocities or accelerations generated by the associated stress waves at that point. Where signals containing relatively high frequency components ($f > 1000$ Hz) are involved accelerometers are usually employed, in contrast low frequency signals ($f < 10$ Hz) are usually detected with displacement gages. Signals between these extremes ($10 < f < 1000$ Hz) are most conveniently detected using velocity gages. Since the following relationships hold:

$$A = \frac{dV}{dt} = \frac{d^2S}{dt^2}$$

where A, V and S are respectively acceleration, velocity and displacement, and t is time, signals recorded in one mode (e.g. velocity) may be electrically converted to the other modes by integration or differentiation. For example, recorded velocity signals may be converted to equivalent acceleration signals by passing them thru a suitable differentiating network.

For microseismic source location purposes either displacement, velocity or acceleration transducers may be used, depending on the frequency of the signals involved. Complications, however, arise when the elements of the transducer array are heterogeneous (i.e. more than one type of transducer in the array, for example, six velocity gages and one accelerometer). These complications are due to the fact that inherent phase shifts* exist between

---

* e.g. for a pure sinusoidal signal the acceleration vector leads the velocity vector by $\pi/2$ radians, and the displacement vector by π radians.

the displacement, velocity and acceleration vectors which must be taken into account when determining arrival times.

The studies described in this report have made use of both accelerometers and velocity gages (geophones). Detailed characteristics of these are given in Appendix C. The majority of the measurements have been made using velocity gages, however accelerometers were utilized as the sensing element in a probe developed for use in boreholes, and in a number of specialized field studies where they were bonded directly to rock surfaces.

2. Geophones

2.1 General

Velocity gages designed specifically for seismic field measurements are generally known as "geophones." This latter term will be used exclusively throughout the remainder of this report. In a geophone an output voltage is generated by a coil of wire moving in a magnetic field (usually the coil is the inertial element and the magnet is fixed to the case). When the device is exposed to movement relative motion occurs between the coil and the magnet, and a voltage proportional to the relative velocity of these parts, is generated.

Geospace model GSC-11D geophones mounted in marsh-type waterproof cases have been used throughout this project. Figure 22 shows a typical unit and detailed specifications are presented in Appendix C. These geophones are available in units with natural frequencies of 8 Hz and 14 Hz. Initial studies utilized the 14 Hz units, however recently the 8 Hz units, which have a somewhat better low frequency response, have been employed. Both units have an intrinsic voltage sensitivity of 0.81 volts/in/sec.

The units were purchased with 20'-30' lengths of waterproof cable (twisted pair) sealed into the marsh-type case through a waterproof gland. After the cables were cut to a suitable length to match the particular

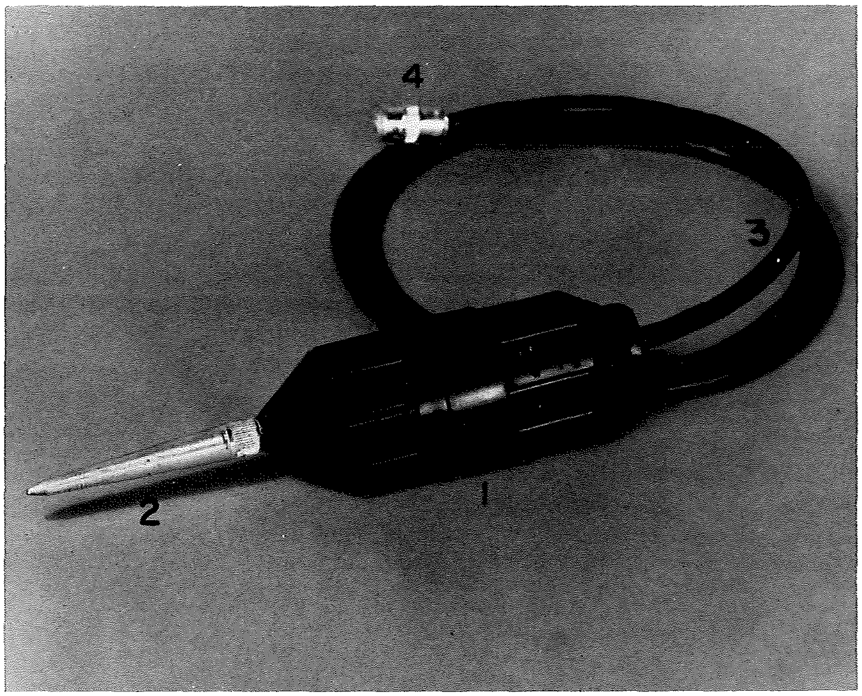


Figure 22 - Typical Geophone Used in Study
(1 - geophone in marsh case, 2 - installation spike, 3 - waterproof cable, 4 - BNC connector)

installation (depth of mounting hole plus 3'-5') a standard male BNC connector was attached.

2.2 Site Evaluation and Surveying

Tentative surface geophone sites were first located on a plan map of the mine at suitable positions relative to the particular study. As a general rule an attempt is made to design the geophone array so that it effectively surrounds the underground area to be studied, with one geophone centrally located. The surface area in question was then investigated and convenient locations, as close as possible to those originally selected were located and marked with numbered wooden survey stakes. In many cases, in the study described in this report, it was impossible to locate the geophones in the exact areas selected from the mine map due to the typically heavy overgrowth present in most areas.

Prior to preparation of the transducer installation holes or sometime after transducer installation, the position and elevation of all geophone locations were accurately surveyed with reference to one or more of the mining company survey monuments.

2.3 Installation Procedure

During this project geophones were installed using three different techniques: surface mounting, shallow burial, and deep burial. Figure 23 illustrates these techniques as well as details of the borehole probe installation which will be described in a later section. It should be mentioned at this point that the deep burial technique has proven to be the most suitable method of geophone installation. It has the important advantages of better coupling with underground activity as well as relative isolation of the geophone from surface noise (vehicular and personnel traffic, tree root noise, wind, etc.).

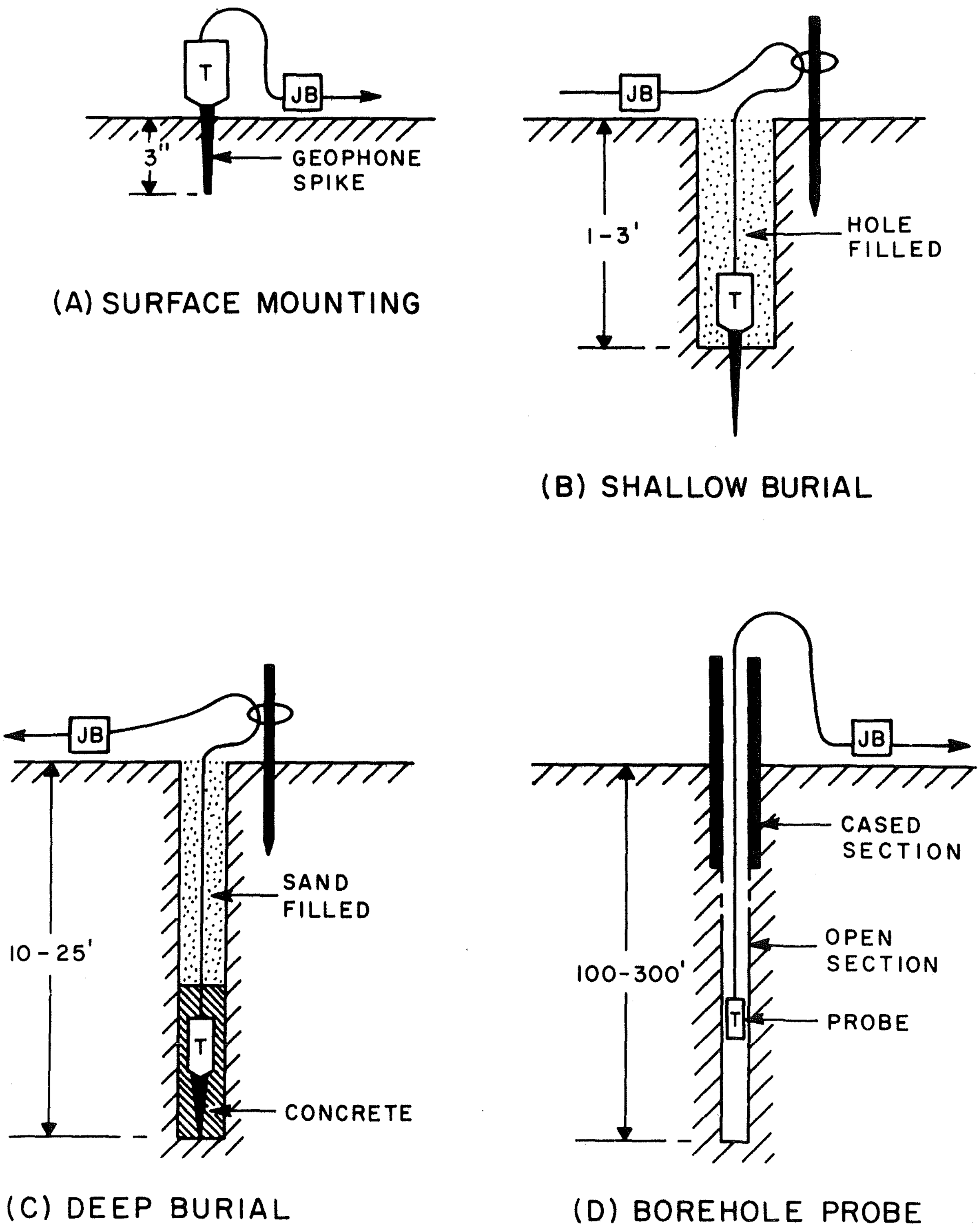


Figure 23 - Transducer Installation Techniques

Surface Mounting of geophones (see Figure 23A) was utilized during a number of the early studies. In this case the spike base of the geophones were pushed firmly into the ground at the required locations. Studies made at the Greenwich A-2 longwall site utilized a linear array of geophones mounted in this manner. This is by far the simplist installation method; however, geophone-to-ground coupling is poor and the geophones are exposed to the prevailing weather conditions.

Shallow Burial Mounting of geophones (see Figure 23B) was accomplished by digging holes approximately 6" diameter and 24"-30" deep in the soil using a hand-operated post hole digger and digging bar. The preparation of such holes was a relatively simple task. In most locations a single hole could be prepared in a matter of 10-15 minutes. In a few instances some problems were encountered due to the presence of subsoil rocks, however, these were easily broken down using the digging bar. Figure 24 shows personnel in the process of preparing a shallow hole installation.

Geophones were usually installed in the prepared holes within a short time (i.e. within an hour or so) after their preparation, otherwise, degradation of the hole could occur making installation difficult. The spike end of the geophone was first driven into the soil at the bottom of the hole, soil was carefully filled-in around the geophone (being sure it remained as vertical as possible), then the remainder of the hole was refilled with soil using the flat head of the digging bar to pack the soil in place after each few inches of soil was added. Great care was necessary to insure that the geophone cable was not damaged during this process.

After the hole was completely refilled a steel fence post or length of steel pipe was driven into the ground six inches or so from the hole to serve as a mounting point for the geophone cable. The cable was firmly fastened to

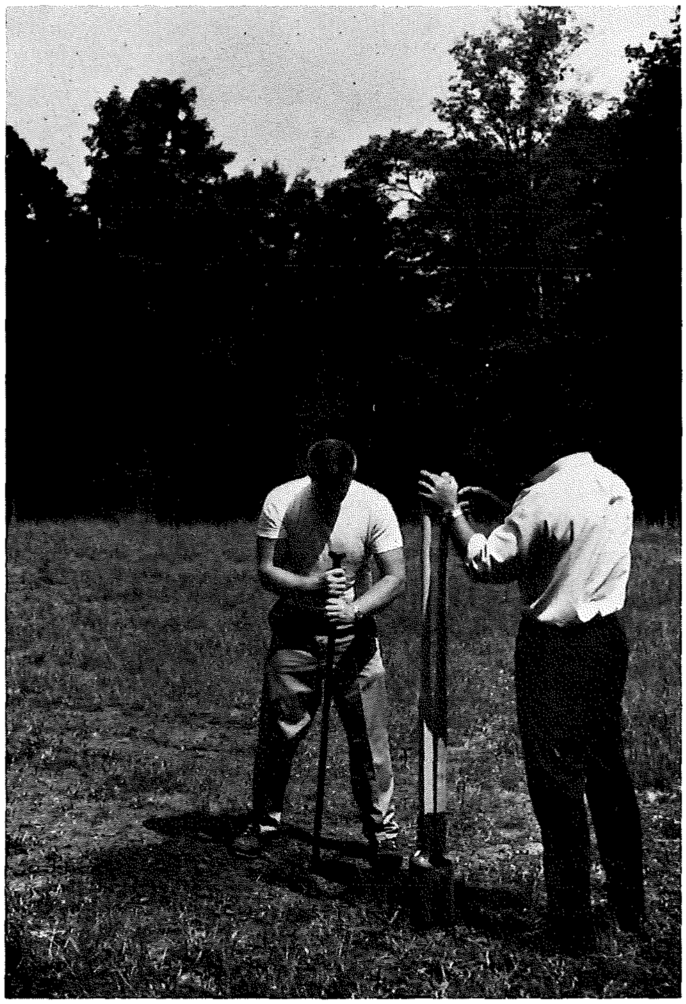


Figure 24 - Personnel Preparing a Shallow Hole for Geophone Installation

the post at a number of locations with electrical tape, and a plastic bag placed over the cable connector and taped upside down to the post. For convenience in locating the geophone locations a length of red surveyors ribbon was attached to the top of the mounting post. Figure 25 shows a photograph of a typical (Greenwich) shallow burial geophone site in Winter.

The shallow burial installation results in improved geophone coupling and protection from the weather as compared with surface installations. However, some studies suggest that background noise due to electrical ground currents may be greatly increased at certain locations when using this installation technique.

Deep Burial Mounting of geophones (see Figure 23C) was accomplished by first augering an approximately 3" diameter hole from surface, through the soil, and approximately 12" into bedrock. In most cases at the Greenwich sites such holes ranged from 10-20' feet in depth. Initially deep burial holes were drilled by project personnel using a semi-portable Winkie drill (see Appendix F). Later holes were drilled commercially* using a truck mounted drilling rig. It should be noted that the Winkie drill has the advantage that it is portable and hence may be operated at sites inaccessible to large commercial drilling rigs. However, from the time point-of-view the Winkie drill is extremely inefficient and commercial drilling is recommended where possible. Figure 26 illustrates both the Winkie and the commercial drilling facilities in operation.

Geophones were installed in deep holes by first carefully lowering the geophone to the bottom of the hole. A number of heavy steel washers strung on the geophone cable insured that the geophone reached the bottom of the hole as vertical as possible. Approximately one half cubic foot of relatively thin

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* Tinney Drilling Company, Pittsburgh, Pa.

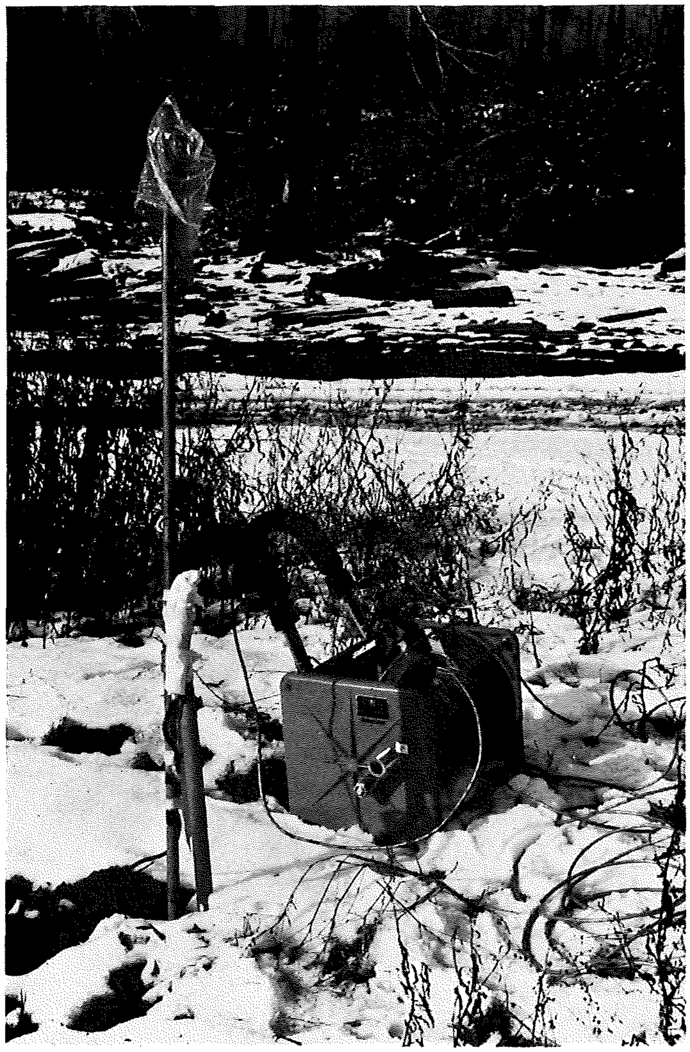
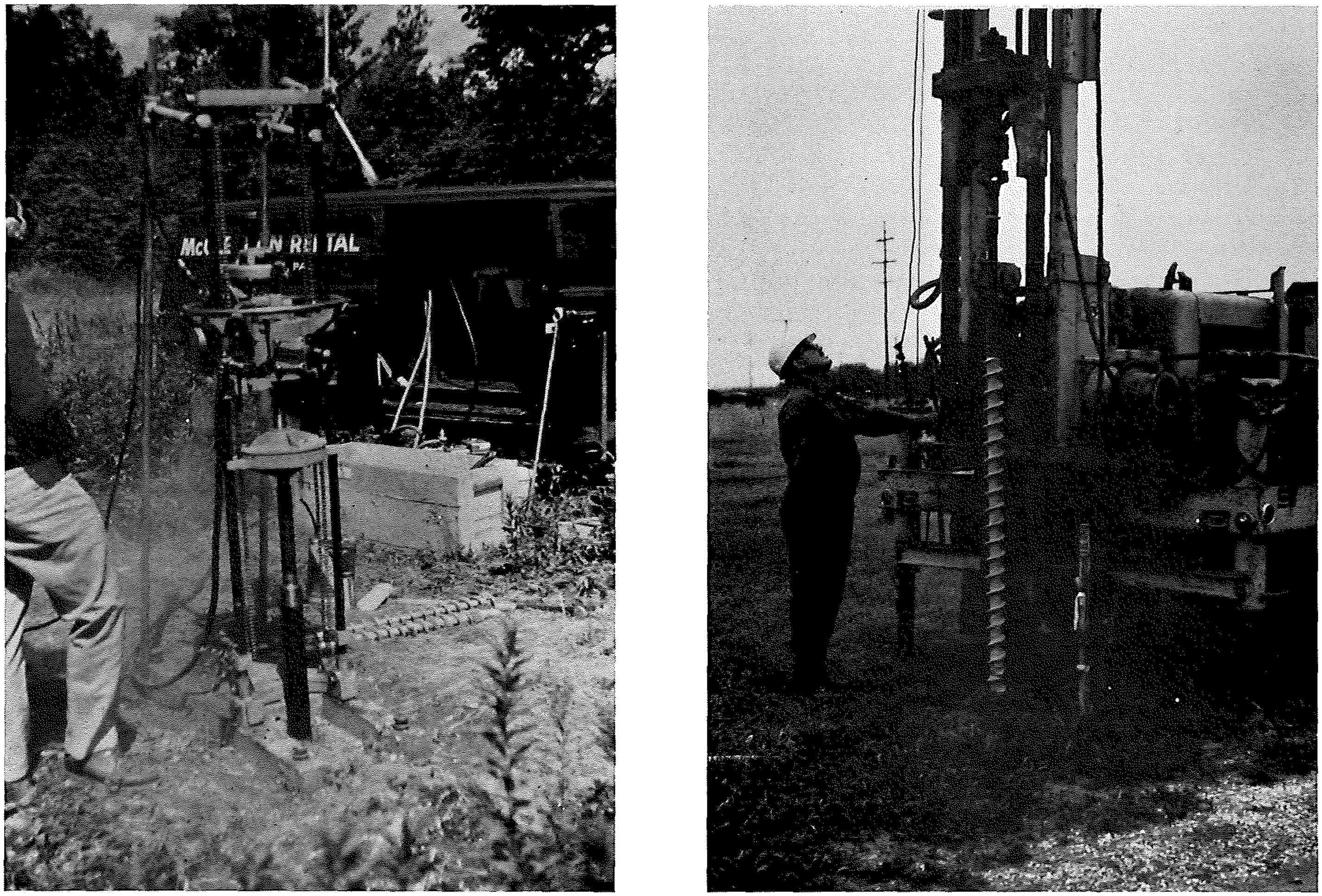


Figure 25 - Shallow Burial Geophone Site in Winter
(Cable reel and line junction box shown,
preamplifier is in insulated package
taped to mounting post)



(A) Winkie Portable Drill (B) Commerical Drilling Facilities

Figure 26 - Drilling of Deep Burial Geophone Mounting Holes

concrete was then poured into the borehole while the geophone cable was held taut. After all the concrete was added a steel fence post was driven into the ground 6"-8" from the geophone hole to serve as a mounting point for the geophone cable. This was taped in place and the connector protected with a plastic bag as in shallow burial installations.

Due to the danger of borehole deterioration in weak soils geophones were installed in deep locations within an hour or so of drilling, otherwise it was necessary to temporarily case the holes until such time as the geophones could be installed. A few days following geophone installation the remainder of the borehole was filled with fine sand to prevent it becoming a sink for surface water. On the surface a typical completed deep burial geophone installation appears similar to a shallow burial one (see Figure 25).

Deep burial installation of geophones appear to be the most suitable of the techniques investigated to date. Since the geophone is actually cemented into the bedrock, coupling is excellent. The geophones are well protected from the direct effects of weather, and the soil layer above the geophone effectively insulates it from surface noise.

3. Borehole Probe

3.1 Introduction

In the previous section the use of geophones--surface mounted, buried in soil or cemented into a borehole drilled in bedrock--have been described. Such installations although satisfactory in many situations have limitations particularly when it is desired to locate a microseismic transducer as close as possible to the coal seam (perhaps a few hundred feet below surface). Since there was a similar requirement for a method of deep transducer installation (at least 300 feet below surface) in another Mineral Engineering Department project* efforts were pooled for the development of a suitable probe that could be conveniently installed in deep boreholes from surface. A detailed discussion of the design, development and field testing of the microseismic borehole probe is presented in a recent internal report [39] by Hardy, Kim and Comeau, a brief outline of which will be included here.

Figure 27 illustrates the general principle of operation and installation of the borehole probe. Basically the probe consists of a rubber-walled inflation chamber which can be expanded by externally applied gas pressure. A microseismic transducer (accelerometer) located inside the chamber is bolted through the rubber wall to a transducer shoe on the outside surface. In use, the probe is located at the desired location in the test borehole and then pressurized. This forces the transducer shoe tightly against the borehole wall, effectively clamping the attached accelerometer in position.

3.2 Development of the Probe

The prototype model of the borehole probe, as shown in Figure 28, was designed by Comeau [40]. It was completed in the Spring of 1972 and laboratory and local field trials on the unit were completed during the Summer. It employed a miniature accelerometer, mounted within an expandable rubber bladder, as the sensing element and was designed for use in BX diamond drill holes. Field tests carried out at a local field site indicated however that a number of refinements in the probe design were necessary. The redesigned probe (Mark II) was completed during the late Summer of 1972 and field testing carried out at a gas storage reservoir site in Northern Pennsylvania during the Fall months.

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* American Gas Association Project PR-12-43, "Optimization of Gas Storage Pressures in Reservoirs."

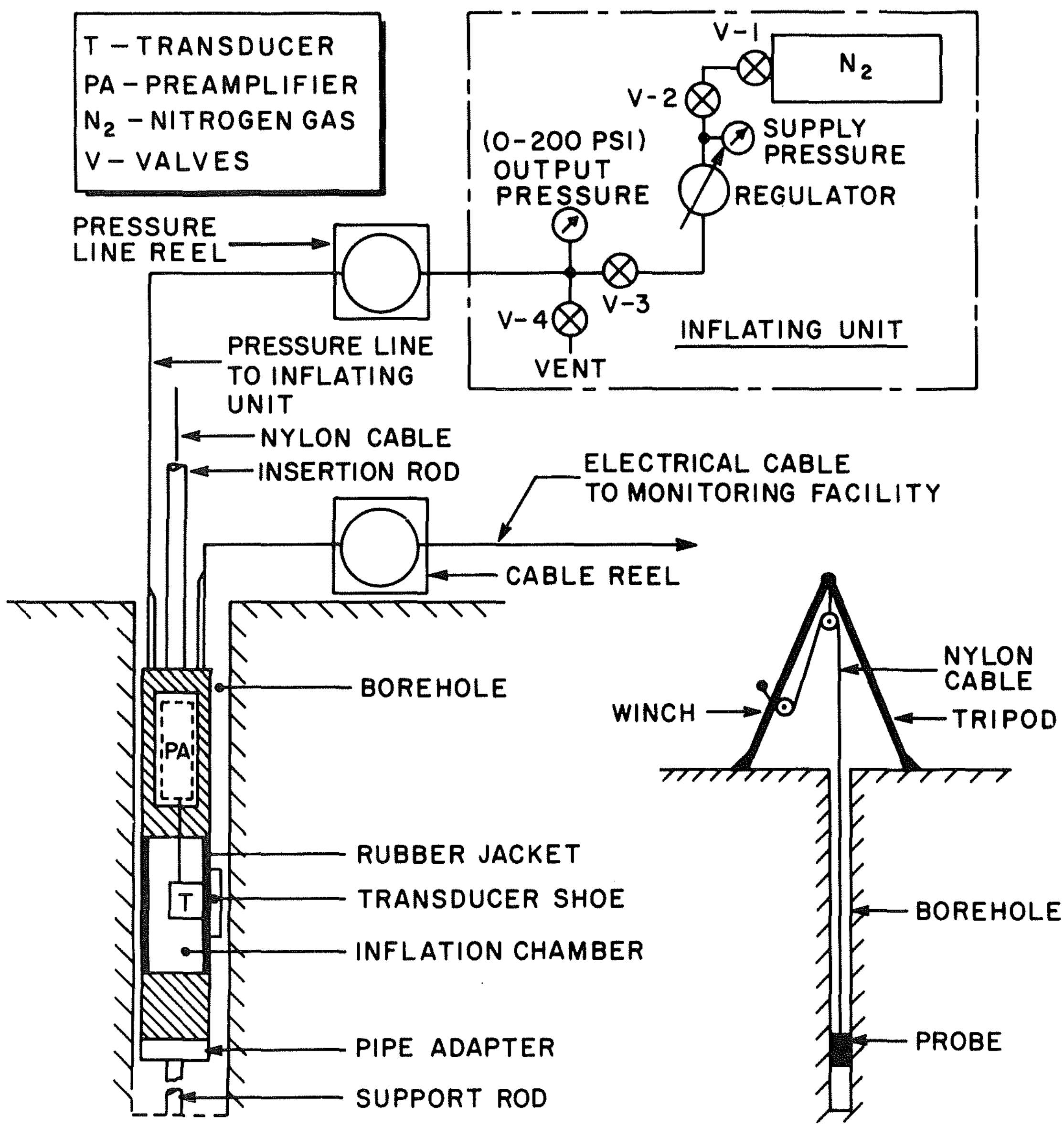
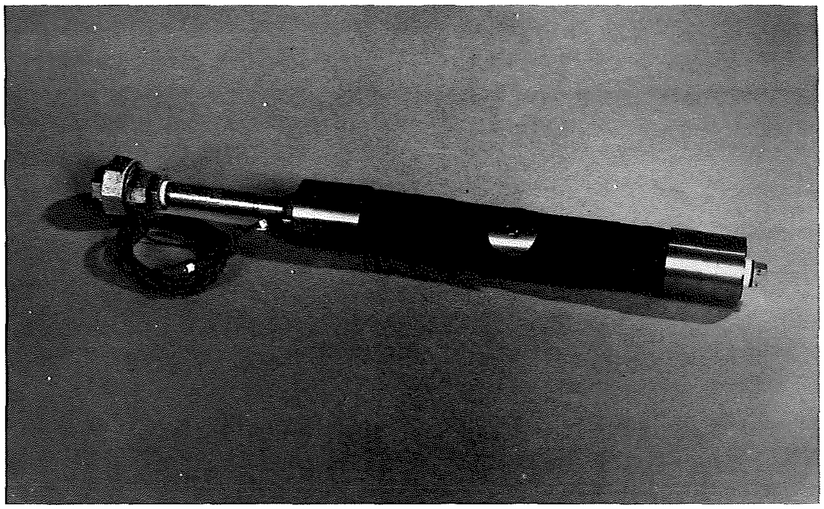
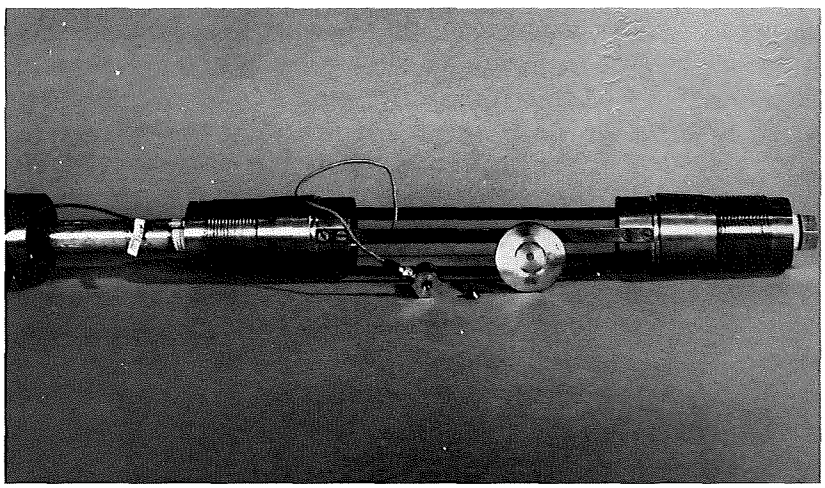


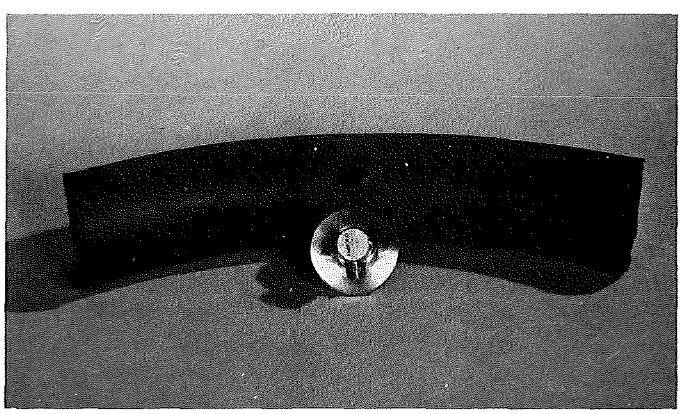
Figure 27 - Principle of Operation and Installation of Borehole Probe



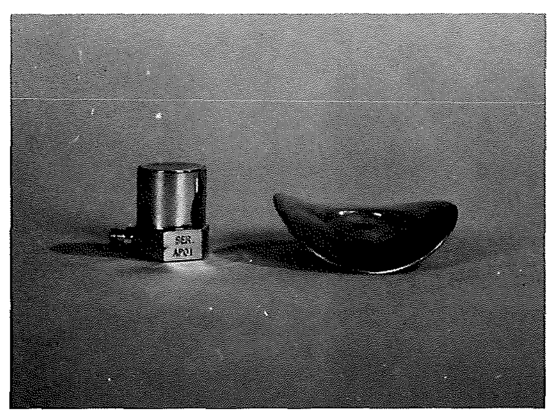
(A) Borehole Probe Assembled



(B) Borehole Probe Disassembled



(C) Rubber Bladder and Accelerometer Attached to Transducer Shoe



(D) Accelerometer and Transducer Shoe

Figure 28 - Prototype (Mark I) Model of Borehole Probe

Figure 29 shows the Mark II model of the borehole probe. The transducer is attached to the inside of the rubber bladder which forms the wall of the pressure chamber. An extruded rubber tube, 1.8 inches in diameter, is employed for the bladder. When nitrogen gas is injected into the probe, it expands the rubber bladder, pressing the transducer shoe (and the attached accelerometer) tightly against the wall of the borehole. Microseismic signals detected by the accelerometer* are amplified first by the preamplifier+ mounted in the probe body and then conducted via water-proof cable to the monitoring facility on surface. The water-proof cable was connected to the output of the preamplifier, through a low pressure male tubing connector which acts as a sealing gland to prevent water from entering the probe. Gas for pressurizing the inflation chamber is supplied by an inflating unit (see Figure 27) consisting of a regulated source of low pressure nitrogen and a series of gages and valves for controlling and monitoring the pressure to the probe. Copper tubbing (1/8 in. O.D.) is used for the pressure line between the probe and the inflating unit. Laboratory tests indicated that it was necessary to pressurize the inflation chamber above 40 psi to obtain satisfactory coupling between the transducer shoe and the wall of the borehole. It should be noted that in the case of water filled boreholes, the differential pressure (pressure difference between the inflation pressure and the pressure due to the water column above the probe) should be at least 40 psi.

Initial field trials of the Mark II unit indicated a number of defects in the probe design as well as a number of general problems inherent in applying the borehole probe concept itself, namely:

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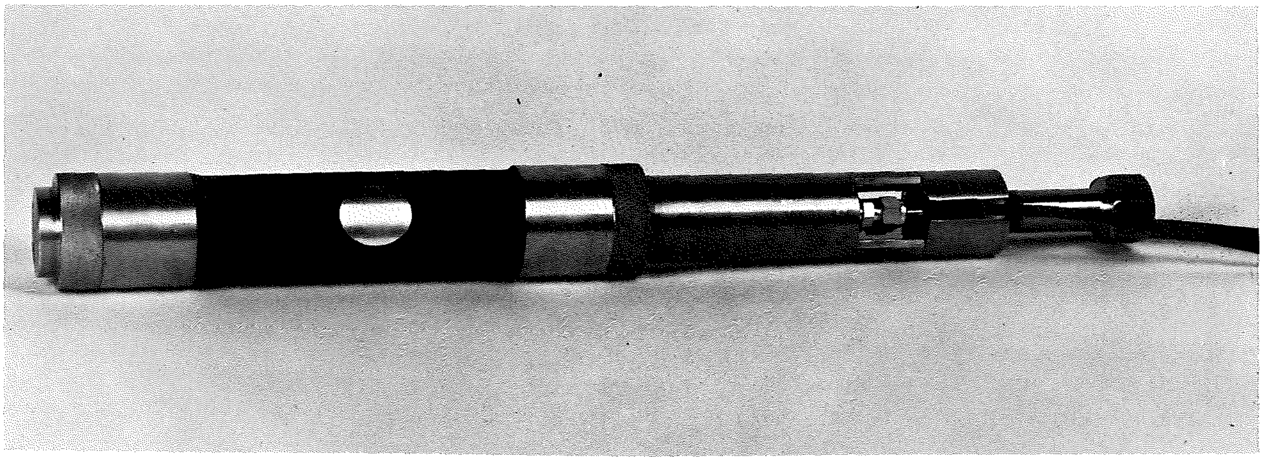
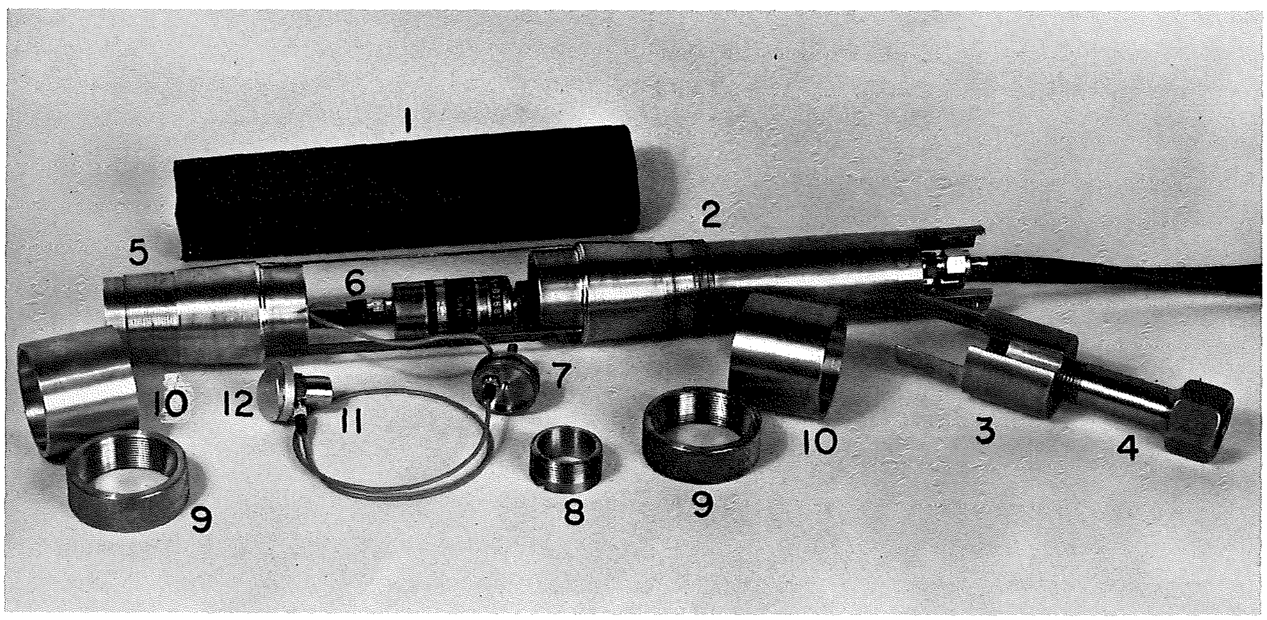
* Endevco model 2233E - see Appendix C for details.

+ Ithaco model 144L - see Appendix A for details.



(A) Probe Assembled Ready for Use



(B) Borehole Probe Disassembled Showing Component Parts [1 - rubber bladder, 2 - probe body, 3 - connecting rod yoke, 4 - pipe adaptor, 5 - probe end-section, 6 - preamplifier, 7 - plug, 8 - plug nut, 9 - bladder clamp nut, 10 - bladder sleeve, 11 - accelerometer, 12 - transducer shoe]

Figure 29 - Mark II Model of Borehole Probe
(Support rod and associated adapter not shown)

(1) Difficulties were encountered with pressure leaks between the rubber bladder and both the transducer shoe and the probe body. Special wrenches were designed to provide better tightening of the seals, eliminating these problems. The seal between the bladder and the transducer shoe however remains a weak point in the cell design.

(2) Aluminum rods originally utilized for installation of the probe were found to be inconvenient for deep installations and were replaced by a nylon rope and an associated tripod and winch.

(3) Early studies indicated that micro-displacements of the probe occurred due to slippage of the transducer shoe along the wall of the borehole. Such displacements resulted in the generation of large pseudo-microseismic signals. To prevent such slippage a section of pipe was connected to a pipe adaptor installed at the lower end of the probe (see Figure 27) to act as a vertical support between the probe and the bottom of the borehole.

(4) The presence of static water in the borehole was found to present no problems however surface or underground water flowing into the probe borehole was found to generate large pseudo-microseismic signals which were difficult to differentiate from true microseismic activity. This problem can be eliminated by casing the probe borehole thru any water bearing zones. Such casing however increases the cost of the probe borehole and prevents microseismic measurements being taken in the cased region.

(5) Casing must also be installed from surface through all regions of unstable strata to insure that borehole integrity is retained. Otherwise the borehole probe may become damaged or trapped downhole.*

In spite of the difficulties and limitations the borehole probe has been found to be an extremely useful tool particularly in that it may be easily installed at various depths in a specific borehole and may be utilized for studies at a number of borehole sites. The Mark II probe (after initial modifications) has no major defects, however in the future some further thought could be given to redesigning the seal between the rubber bladder and the transducer shoe.

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* Insufficient depth of casing was initially installed in the Greenwich mine air return site probe borehole. During preliminary studies the probe became jammed in a deteriorated section of the borehole and considerable effort was required to free the probe, which was damaged in the process.

3.3 Installation Procedure

Figure 27 presented earlier illustrates diagramatically the probe installation technique. A suitably cased BX diamond drill hole must first be prepared in the required test area. A commercial drilling firm* has been utilized for this work to date. Diamond core drilling is recommended for two reasons; first a better quality hole is obtained, and second drill core is obtained which may be used in evaluating the physical properties of the overlying strata.

In general the probe installation would proceed as follows:

(1) The protective cover is removed from the borehole casing and the installation tripod set-up over the borehole.

(2) The depth of water in the hole is measured using a commercial water level indicator.+

(3) The borehole probe and the associated reels containing the electrical cable and the copper pressurization line are moved into position near the borehole.

(4) The inflating unit is connected to the pressurizing line, and a suitable source of nitrogen gas connected into the inflating unit.

(5) The nylon lowering cable is passed over the tripod pulley and the attached mounting fixture coupled into the pipe adaptor at the top of the borehole probe. Figure 30 illustrates the borehole probe installation at this stage.

(6) The required length of support rod is attached to the lower end of the probe. This fixes the final position of the probe in the hole.

(7) The probe is then inserted into the borehole casing as shown in Figure 31 and the electrical cable and pressurization line carefully fed into the casing as the cell is slowly lowered to the desired depth, which is determined normally by the length of the support rod (see item 6).

(8) The electrical cable from the probe is connected into the primary cable to the monitoring facility.

(9) The nylon cable is relaxed.

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* Tinney Drilling Company, Pittsburgh, Pa.

+ Soiltest model DR-760A water level indicator.

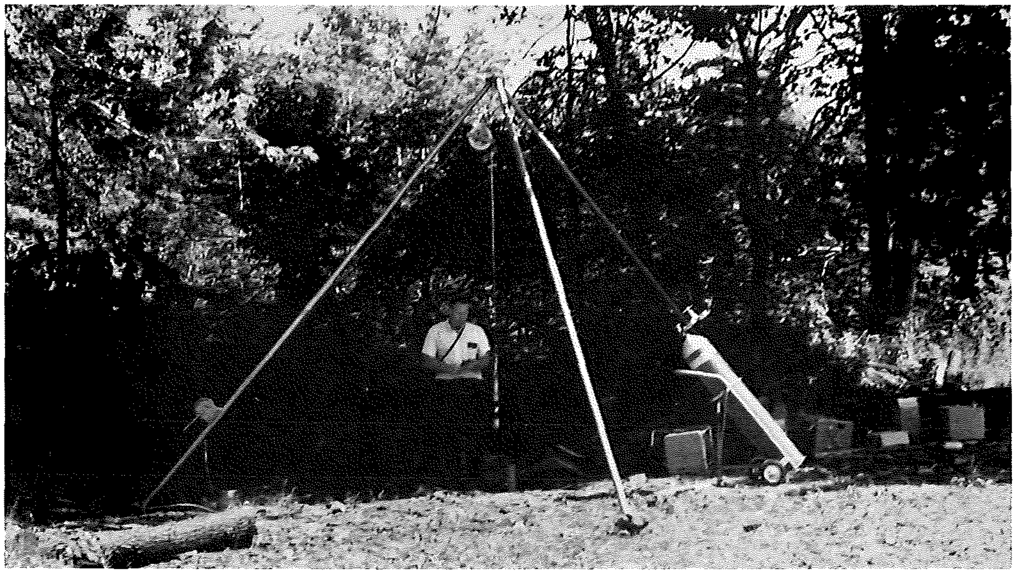


Figure 30 - Borehole Probe Installation at Greenwich Air Return Site

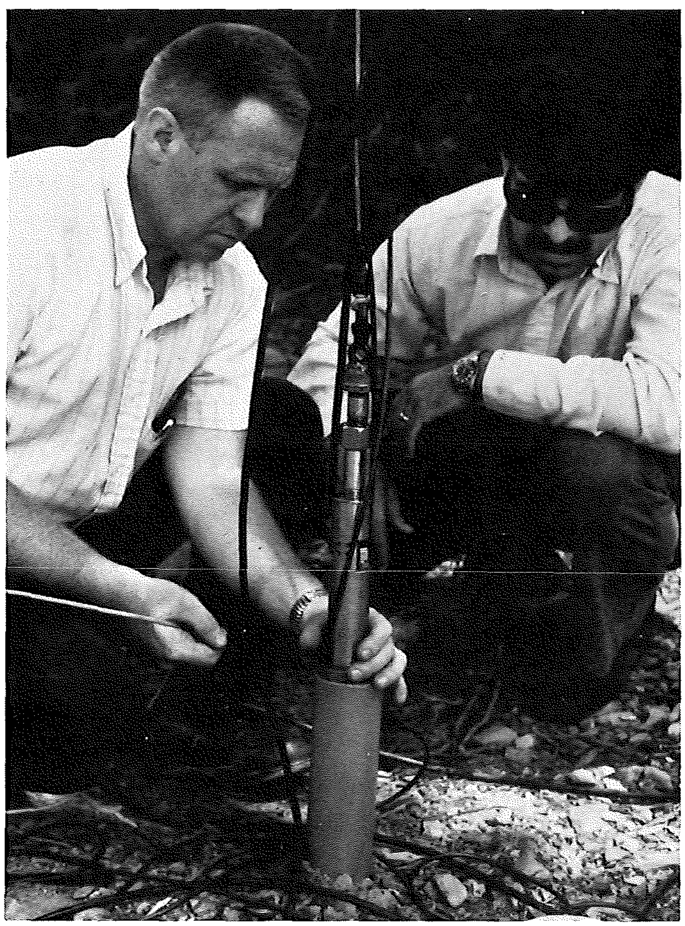


Figure 31 - Inserting Probe into Borehole Casing

(10) Inflating pressure is then slowly applied to the probe up to a value calculated for the specific location (approximately 40 psi over the ambient pressure* at the probe position). The application of inflating pressure would proceed (see Figure 27) by insuring first that the regulator was set to its minimum value and all valves were closed. Valves V-1 and -2 are first opened then V-3. The regulator output is then increased slowly up to the desired level as indicated on the output pressure meter. To check for leaks in the pressurizing line and/or the probe, valve V-3 is shut-off and the output pressure gage observed for a period of time. Any leak will result in a drop in output pressure. Assuming no leak is detected valve V-3 is again opened and the probe is ready for use.

(11) Normally the electrical output of the borehole probe is monitored during pressurization. As the transducer shoe contacts the borehole surface and comes into mechanical equilibrium, a series of pseudo-microseismic signals will be generated. These decrease in frequency and magnitude and eventually cease as equilibrium is reached.

4. Field Transducer Wiring

4.1 Electrical Details

As distinct from permanent transducer cable installations commonly used in underground microseismic mine studies, current field studies use temporary surface cable connections. These are installed for a specific series of measurements and removed when the measurements are completed (very often during the same day). Figure 32 illustrates a typical geophone wiring arrangement, and Figure 33 shows the various components. At present distances between the monitoring facility and any individual transducer is limited to approximately 1500' as established by the permissible preamplifier voltage supply drop in the cables. For distances up to 1000' only a single 1000' cable would be required [in this case the output of junction box JB-1 would connect directly

* Ambient pressure is normally only that due to the hydrostatic head in the borehole, which has an average gradient of 0.43 psi/ft. For example if the probe were to be located at a position where there was 100 feet of water above the cell, the ambient pressure would be 100 x 0.43 = 43 psi, and the inflating pressure should be set at approximately 43 + 40 = 83 psi.

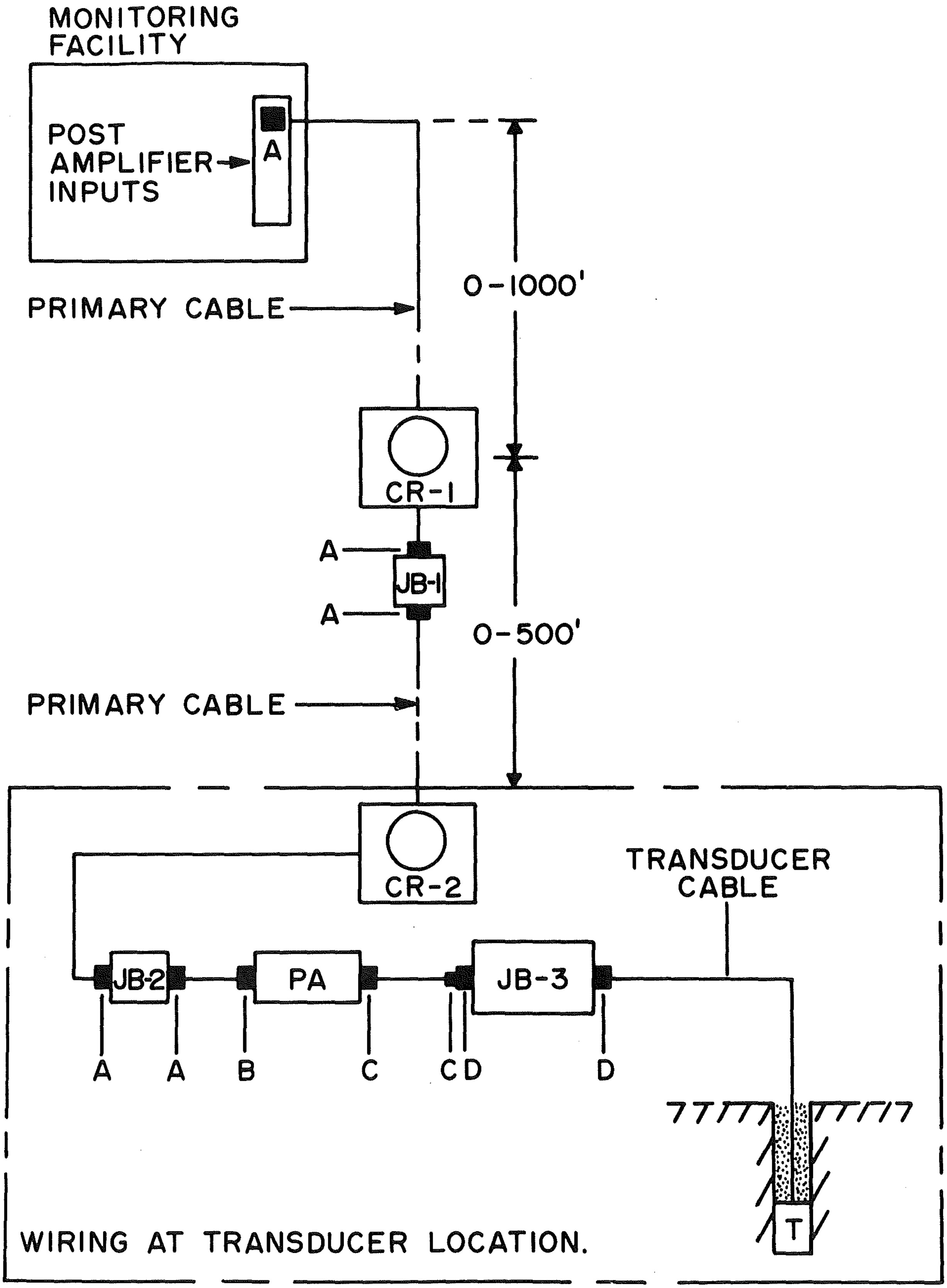
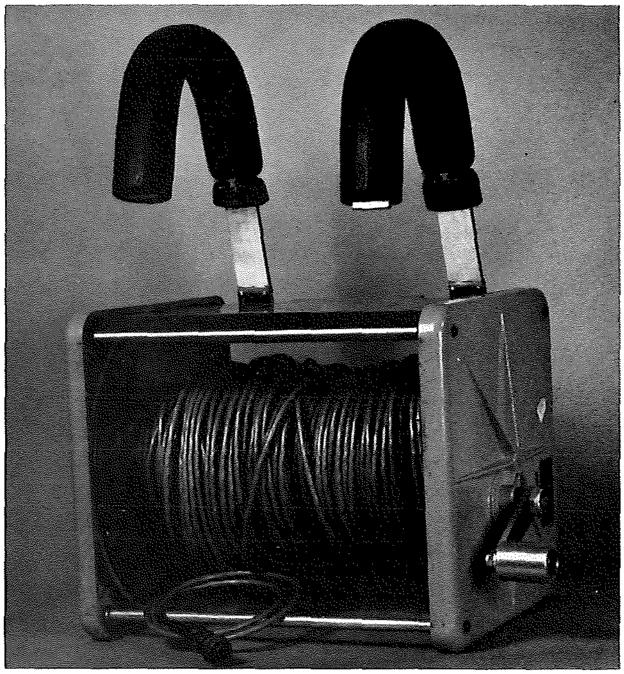
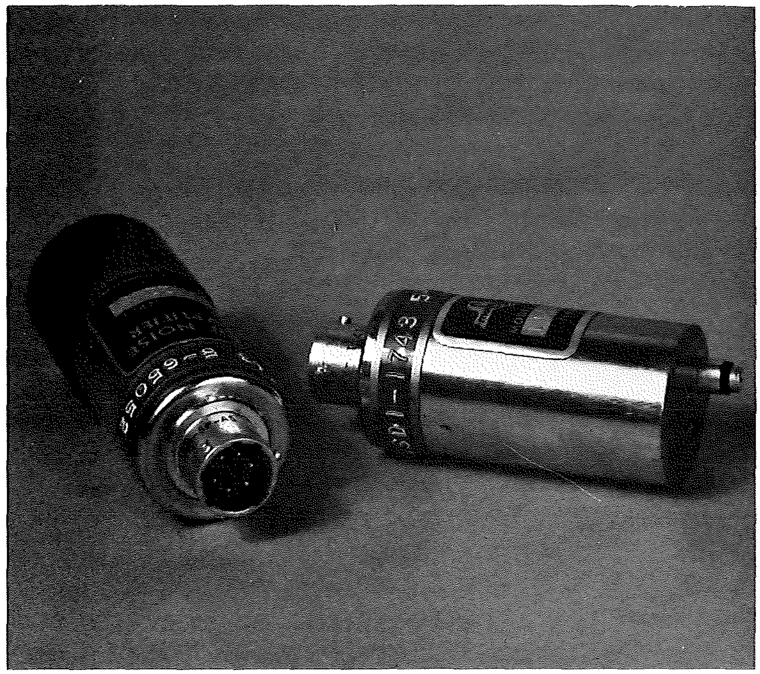


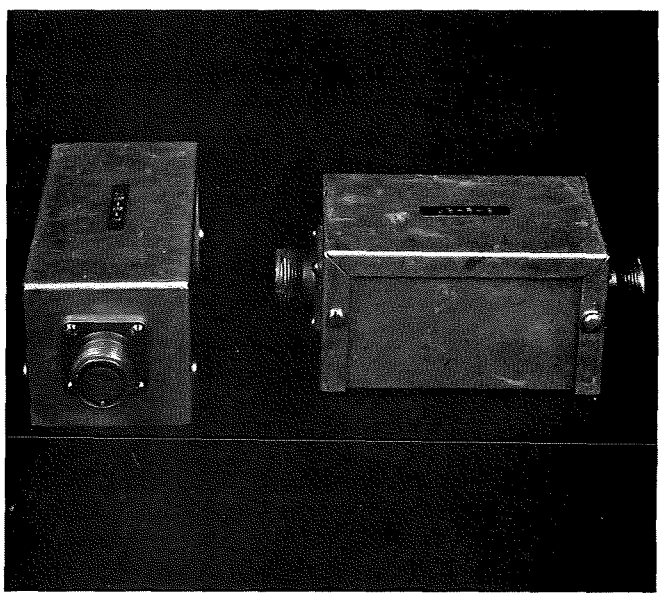
Figure 32 - Typical Field Wiring Arrangement



(A) Cable Reel



(B) Preamplifiers



(C) Line Junction Boxes

(D) Transducer Junction Boxes

Figure 33 - Components of Field Wiring Used for Surface Monitoring

into the preamplifier (PA)]. For the maximum transducer distance (1500'), a 1000' cable plus a 500' cable would be utilized as shown in Figure 32.

The primary cables* have been made up in 100', 200', 500' and 1000' lengths. They consist of lengths of Alpha #6010* PVC covered cable containing three twisted and individually shielded pairs with six pin male connectors* on both ends. Figure 34 shows the wiring arrangement used for the primary cables. For convenience in field wiring, the 500' and 1000' primary cables are mounted on cable reels*. As shown in Figure 32, one end of each of these cables plugs directly into the post amplifier rack in the monitoring facility, and the other end plugs into a line junction box (JB-1 or JB-2). A short (six conductor) cable connects the line junction box to the output of the preamplifier (PA) and a short (single conductor) shielded cable with male microdot connectors connects the input of the preamplifier to the transducer junction box (JB-3). The transducer cable itself is waterproof and contains a twisted pair terminated in a male BNC connector which connects directly into the transducer junction box (JB-3).

In the original design the transducer junction box merely provided convenient means for connecting the transducer cable to the preamplifier. A more recent design, however, incorporates a number of other functions, namely (a) selection of the geophone damping resistor and (b) filtering for rejection of high frequencies. Figure 35 shows a circuit diagram of the present transducer junction box. Signals from the geophone input to the unit via a female BNC connector (J-1), pass through a simple RC-filter (consisting of R_1 and C_1), and output to the preamplifier via another female BNC connector (J-2). A second output connection (J-3) is available for those cases where a geophone

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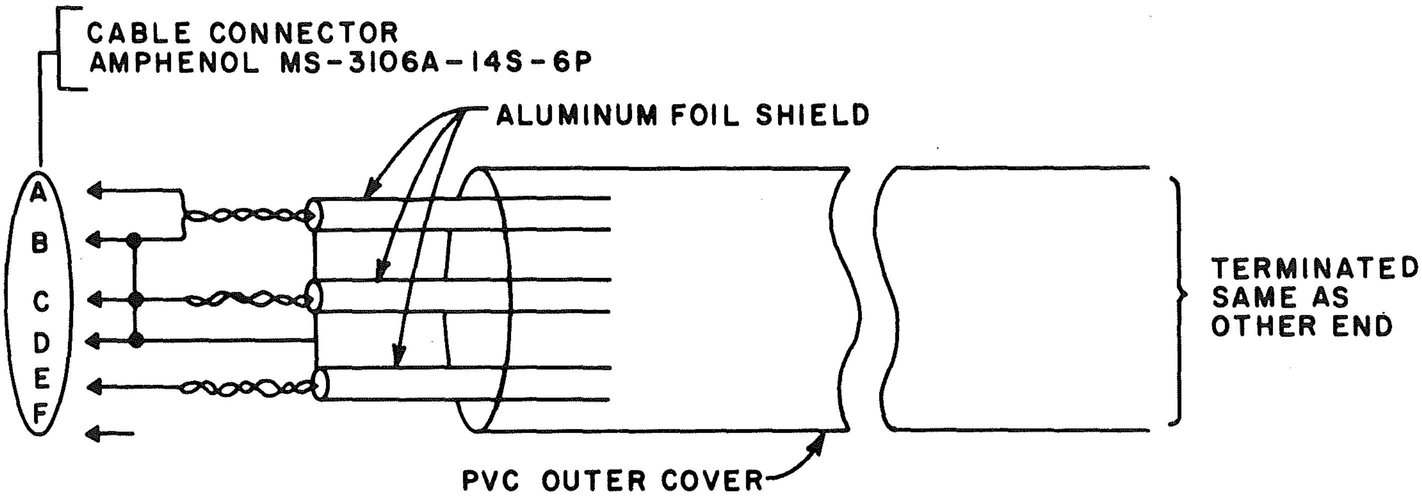
* See Appendix A for details.



PIN A	SIGNAL LEAD – RED		ONE TWISTED PAIR
PIN B	SIGNAL COMMON – BLACK		
PIN C	PREAMP POWER COMMON – GREEN & BLACK		ONE TWISTED PAIR
PIN D	SHIELD COMMON – ALL SHIELD DRAINS TWISTED TOGETHER AND TERMINATED AT THIS PIN		
PIN E	PREAMP POWER PLUS – BLACK & WHITE		ONE TWISTED PAIR

Figure 34 - Wiring Diagram for Primary Cables

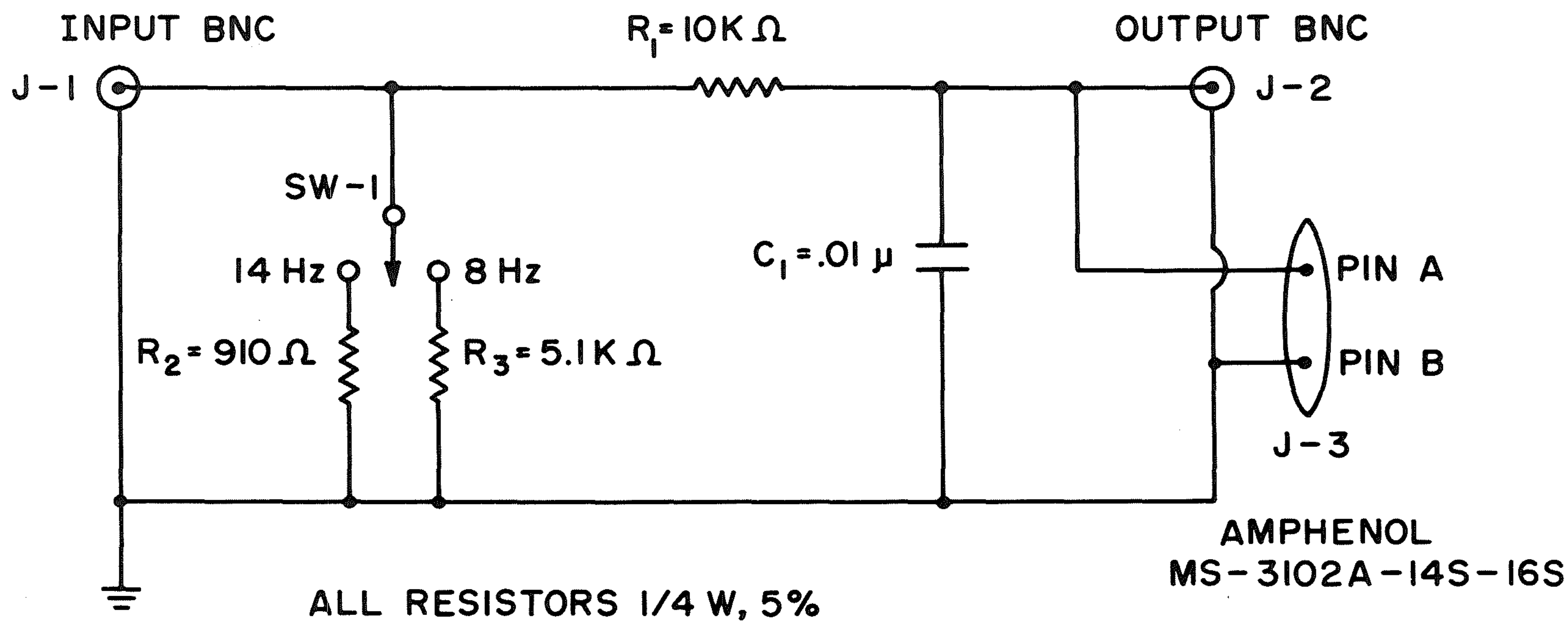


Figure 35 - Circuit Diagram of Transducer Junction Box (Mark-1)

is used without a preamplifier. In this case the connector on the primary cable can mate directly with the transducer junction box via connector J-3. Figure 36 shows the characteristics of the built-in filter. This was added to the system to reduce the high frequency content of the background noise which sometimes caused preamplifier saturation. Switch SW-1 located in the transducer junction box allows selection of the proper geophone damping resistor (i.e., 8 Hz - 5.1 KΩ, 14 Hz - 910 Ω).

All cable reels, short cables, junction boxes, and preamplifiers are numbered. During every experiment the numbers of the particular units utilized for each monitoring channel are recorded. In this way the presence of any defect in the overall field wiring arrangement may be quickly isolated. It should be noted that the present arrangement, where the preamplifier (PA), and the junction boxes (JB-2 and JB-3) are all separate units enterconnected by cables, will be modified in the future. It is planned to incorporate all the necessary features into a single moisture-proof enclosure with a BNC input connector, for connection to the transducer cable and an output connector to mate directly with the connector on the primary cable.

4.2 Cable Installation Procedure

Regardless of the type of microseismic transducer installation involved (surface, shallow burial or deep burial geophone, or borehole probe) the cable installation procedure is basically the same. The field wiring arrangement illustrated earlier in Figure 32 is used for all geophone lines. If the borehole probe is in use the wiring for that particular line is slightly different since the preamplifier itself is mounted within the borehole probe. In this case there is a 300' length of special waterproof cable connected permanently to the borehole probe. This cable terminates in a male connector which mates with the connector on a standard line junction box. In other words, referring

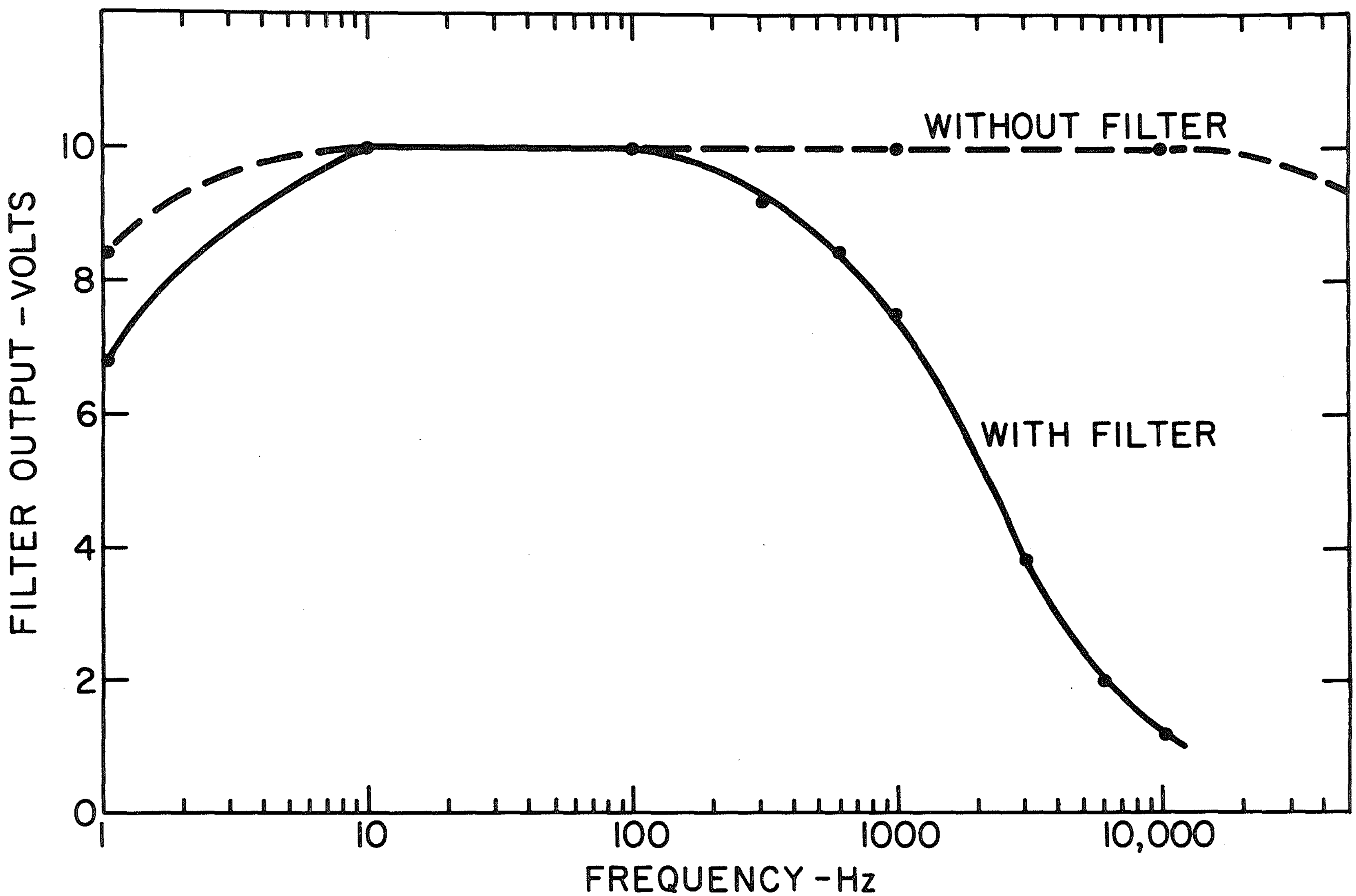


Figure 36 - Characteristics of Transducer Junction Box Filter

to Figure 32 the cable from the borehole probe would plug directly into junction box JB-1, and the remainder of the wiring back to the monitoring facility would remain the same as that used for geophones.

Assuming that the various geophones and/or borehole probe are in place, the cable installation would proceed as follows:

(1) Cable reels, containing 500' and 1000' lengths of cable, as well as loose short lengths of cable (100' and 200') are unpacked.

(2) Distances and most suitable paths between the monitoring facility and the various transducer locations are checked and a decision as to the most suitable cable arrangement for each location is made (e.g. distance is 650' - use 1-500' reel plus 1-200' loose cable, etc.).

(3) For each cable line the free end of the reel cable as well as the reel itself is tagged to correspond to the associated transducer location (e.g., #4). Masking tape and a felt pen are used for this purpose. If the cable run exceeds the length of the cable on the first reel and a second reel or short length of cable must be added, then these additional cables are also tagged in the same manner.

(4) Cable is run-out from the monitoring facility towards the transducer location. It is necessary that enough free cable be available at the facility to connect (without cable strain) into the post amplifier inputs on the rear of the monitoring rack. Care must also be taken to keep cables free of vehicular or personal traffic to reduce the possibility of cable damage.

(5) Once the cables themselves are in place the necessary line junction boxes are added, followed by the appropriate transducer junction boxes, preamplifiers, and cables at each transducer location.

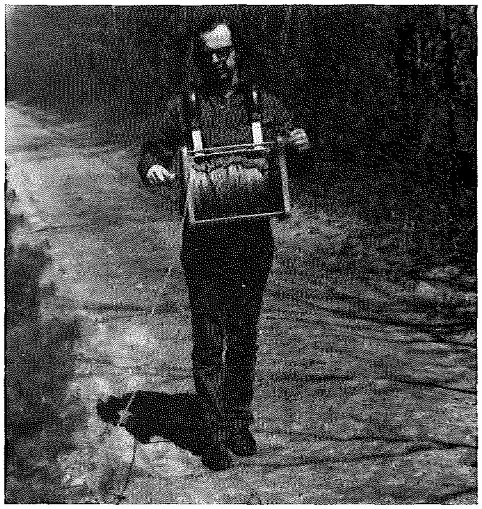
(6) In the case of each geophone installation the appropriate damping resistor is selected by setting the switch in each transducer junction box to either the 8 Hz or 14 Hz position.

(7) Components at the transducer locations are protected from the weather as much as possible by placing them under the shelter of the cable reel or wrapping them in a plastic bag.

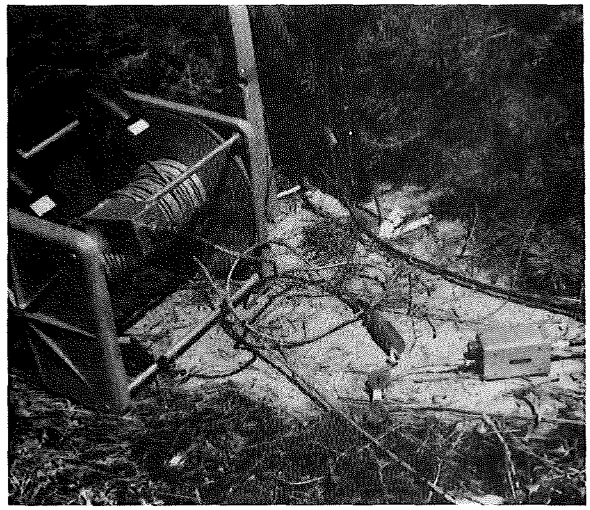
(8) Once the monitoring electronics have warmed up, the operation of each transducer channel is checked (background amplitude and frequency content) over a period of time to insure there are no intermittants in the lines. If not, then the transducer wiring is complete and ready for use.

(9) Following installation or during removal of the transducer wiring a record is taken of the serial numbers of all components (cables, junction boxes and preamplifiers).

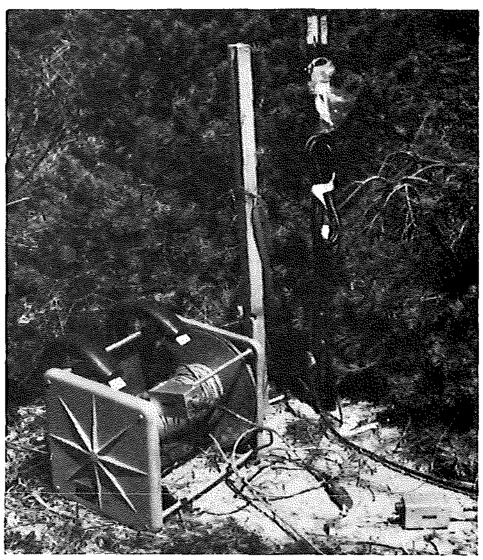
Figure 37 shows a number of stages during the installation of the field transducer wiring. In those cases where measurements are planned at specific locations for a period of time (e.g., one day, once a week for a month) the cable reels and all associated components (junction boxes, preamplifiers, etc.) are sealed inside heavy plastic bags (see Figure 37D). This type of protection has been found to be satisfactory even during winter months.



(A) Running Out Transducer Cable



(B) Components at Transducer Location



(C) Typical Transducer Location

(D) Weather Proofing at Borehole Probe Location

Figure 37 - Various Stages of Field Transducer Wiring

DATA ANALYSIS PROCEDURES

1. Introduction

There is little doubt that the analysis of microseismic field data in the current project has lagged far behind the actual acquisition of such data. For the most part this has been due to the following factors:

(1) Many of the field studies were carried out in order to develop experimental techniques (e.g. transducer installation). Once the technique itself was evaluated it was necessary to move as quickly as possible to a new field site to keep up with the area being mined. As a result detailed analysis of collected data was delayed.

(2) In general it was necessary to take advantage of suitable mining situations where and when they occurred. As a result, if an interesting mining sequence appeared imminent, a transducer array was installed and measurements were taken regardless of the existing backlog of microseismic data.

(3) Analysis techniques themselves have been under consideration and in particular considerable effort has been expended in developing computer based techniques for rapid analysis of multi-channel data. It was considered more efficient therefore to delay detailed analysis until the required analytic methods had been developed.

Suitable methods of data analysis have only been developed in recent months. As a result detailed analysis of the various field studies will be delayed until preparation of the final report for the second part* of the overall coal mine microseismic study, which is presently in progress. In this chapter data analysis methods utilized in this project will be reviewed along with a brief description of the recently developed computer based analysis methods.

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* USBM Project G0144013, "Microseismic Monitoring of a Longwall Coal Mine" scheduled for completion September 30, 1974.

2. Manual Analysis System

As has been noted earlier the prime purpose of the mobile microseismic monitoring facility was to record field data for later analysis in the laboratory. To date the majority of such analysis has been done "manually." Figure 38 illustrates the system* used. Initial editing of the field data is carried out as shown in Figure 38A. Here data recorded on tape recorder No. 1 in the field was played back through amplifiers and filters into either a UV-recorder, tape recorder No. 2 or both. Such play-back may be accomplished for up to seven channels simultaneously. The UV-recorder provides permanent chart records (hard copy) of the field data which may be examined for the presence of specific types of microseismic events or in order to study ambient background characteristics. At this stage in the analysis the tape footage of each feature of interest was logged for future reference. Normally when operating directly into the UV-recorder the replay tape speed was increased considerably over the original recording speed in order to compress the UV-recording in time and thus provide a convenient length of hard copy. When a set of microseismic events of particular interest were noted on the hard copy then the appropriate sections of tape were replayed at different speeds and at various filter settings in order to study these events in more detail. For example this arrangement has been utilized to carry out simple frequency analysis of specific signals by replaying these for a number of filter settings and measuring the change in amplitude of the signal on the UV-recordings.

The editing circuit also provides a convenient means of actually "editing" the original field data so that only specific sections are re-recorded on tape

* Tape recorder No. 1 and the UV-recorder are both located in the mobile monitoring facility. The post amplifier (AMP) and filter (FILT) are similar to those used in the mobile facility. Details of the other units in the manual analysis system are given in Appendix G.

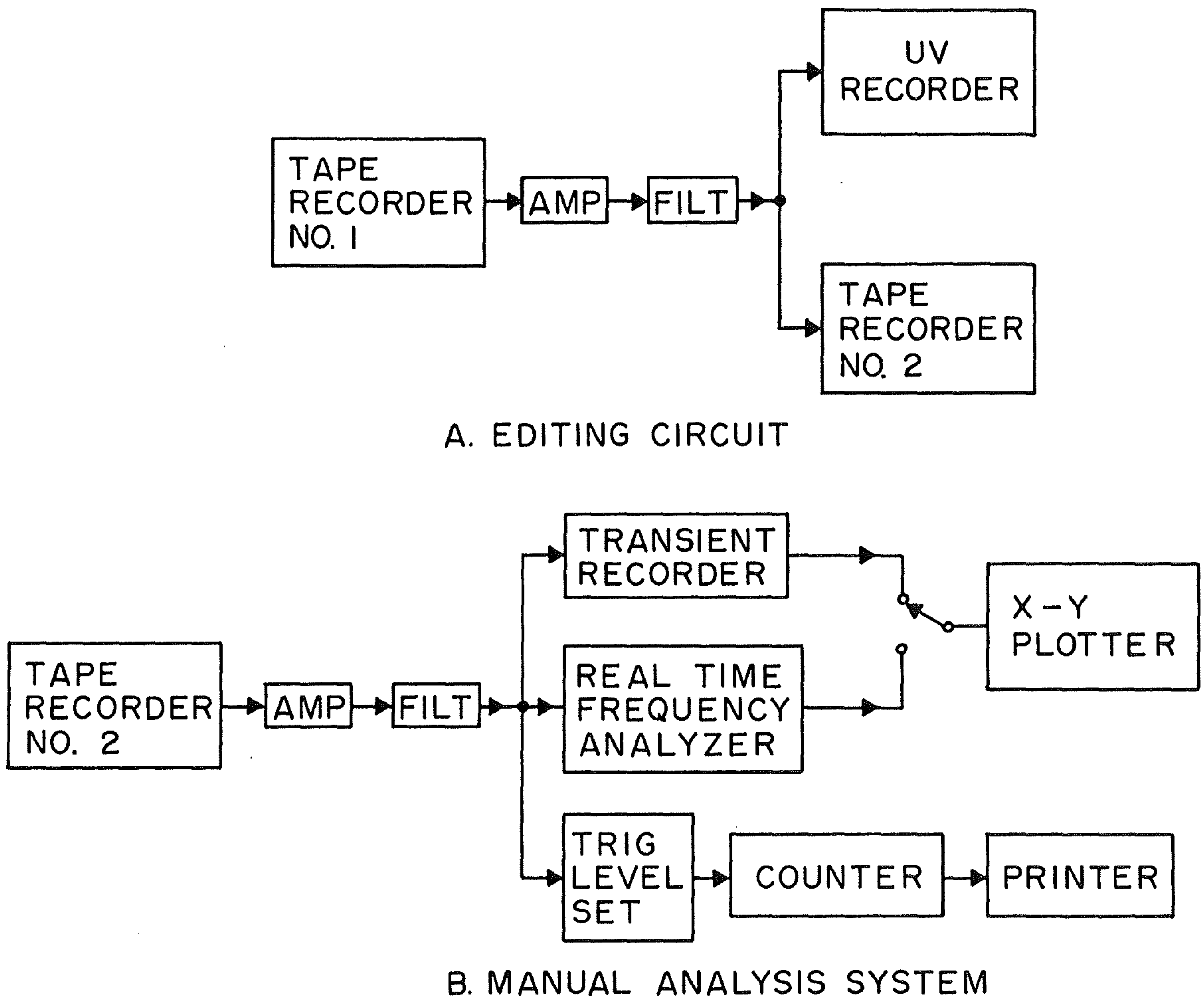

Figure 38 - Block Diagrams of the Editing and Manual Analysis System

recorder No. 2 for further analysis. For example sections of data containing signals due to known culteral noise (e.g. trucks and cars, mine machinery, electrical transients, etc.) may be eliminated. Such editing is a prerequisite for later manual or computer analysis.

For more detailed analysis of field data the system illustrated in Figure 38B was employed. Here field data re-recorded on tape recorder No. 2 during editing may be analyzed by a variety of techniques. It should be noted that until recently (when tape recorder No. 2 was acquired) the output of tape recorder No. 1 was played directly into the analysis system without prior editing. The manual analysis system incorporates the following units:

(1) A transient recorder, so that selected microseismic signals may be "captured" and recorded on the x-y plotter,

(2) A real-time frequency analyzer, so that either individual microseismic signals, groups of such signals, or ambient background signals may be analyzed for frequency content and the resulting frequency spectra recorded on the x-y plotter, and

(3) A digital counter and associated printer, so that the total number of microseismic events above a specific magnitude (defined by Trig Level Set), or the rate of occurrence of such events during a specific interval may be recorded.

It should be noted that the manual analysis system allows only one channel of data to be processed at a time.

Basic microseismic data obtained at various Greenwich test sites, as well as typical examples of such data after processing with the manual analysis system are presented later in the "Field Studies" chapter of this report.

3. Hybrid Computer Analysis System

A computer based analysis system, utilizing the Penn State Hybrid Computer Facility, has been under development for some six months [41]. A simple block diagram of this system is shown in Figure 39. Here edited field data (7 channels) may be played directly into the analog section of the computer,

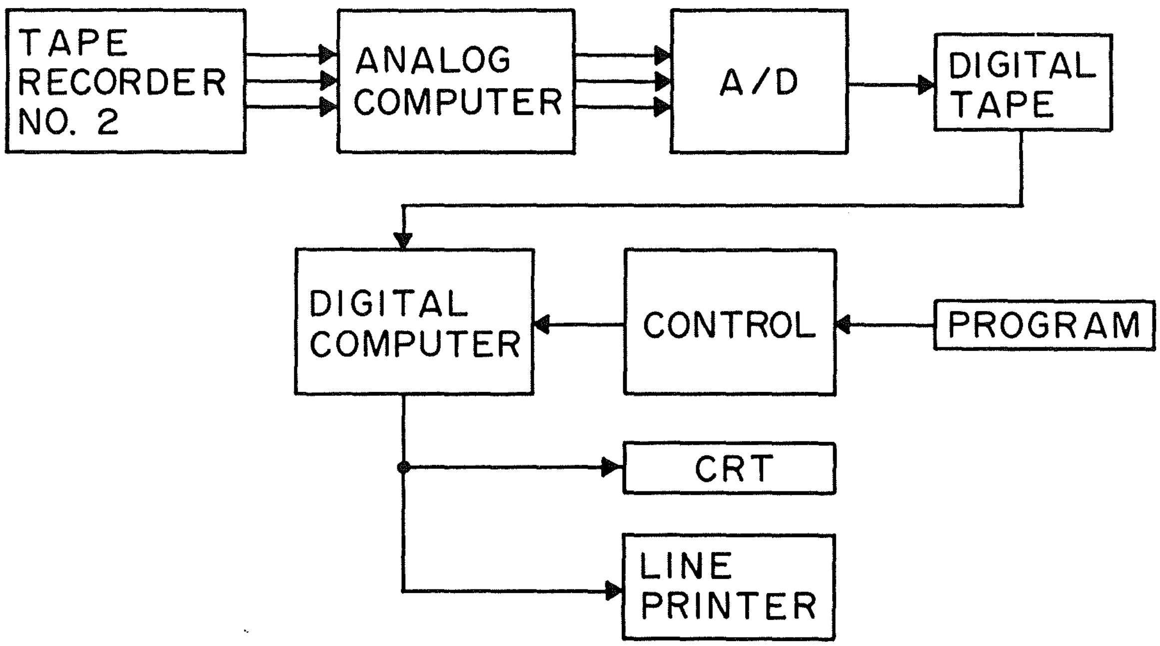

Figure 39 - Hybrid Computer Analysis System

analog processing (if necessary) carried out, and the resulting signals digitized and placed on digital tape within the computer. This digitized data may then be processed in a variety of ways, and results displayed on a CRT, line printer, or other output device. To date, programs for interfacing the field data to the system, and for frequency analysis, auto-correlation, cross-correlation, and amplitude density of selected sections of data have been developed and "de-bugged." During the next few months this analysis system will be utilized for the detailed evaluation of microseismic field data collected at a number of Greenwich mine field sites during the last 18 months.

MICROSEISMIC FIELD STUDIES

1. Field Site

1.1 Introduction

During the Spring of 1971, the project director visited a number of coal mine properties in Central Pennsylvania in search of a suitable site for microseismic field studies. Based on a number of factors, including the mine management's strong interest in cooperating with the project personnel, the Greenwich Colliery, located near Barnesboro, Pennsylvania, was selected. Figure 40 illustrates the general location of the field site and its relationship to the project base at The Pennsylvania State University.

1.2 Description of General Area

An excellent brief description of the Greenwich area was prepared by Yonkoske in 1972 [42] and is included in the following sections.

Topography: The property of Greenwich Collieries Company is located on the eastern part of the Appalachian Plateau in the middle of Pennsylvania. The Appalachian Plateau is primarily an area of low relief. About 25 miles to the east is a steep erosional scarp, called the Allegheny Topographic Front (see Fettke [43]), which separates the Appalachian Plateau province from the Valley and Ridge province of Pennsylvania.

The mine is located at an outcrop of the Lower Freeport "D" coal seam just north of the village of Greenwich and 2 miles from Barnesboro, Pennsylvania. The west branch of the Susquehanna River, which flows to the north, provides the primary drainage pattern in the area. Local geologic and topographic features are depicted on Figure 41.

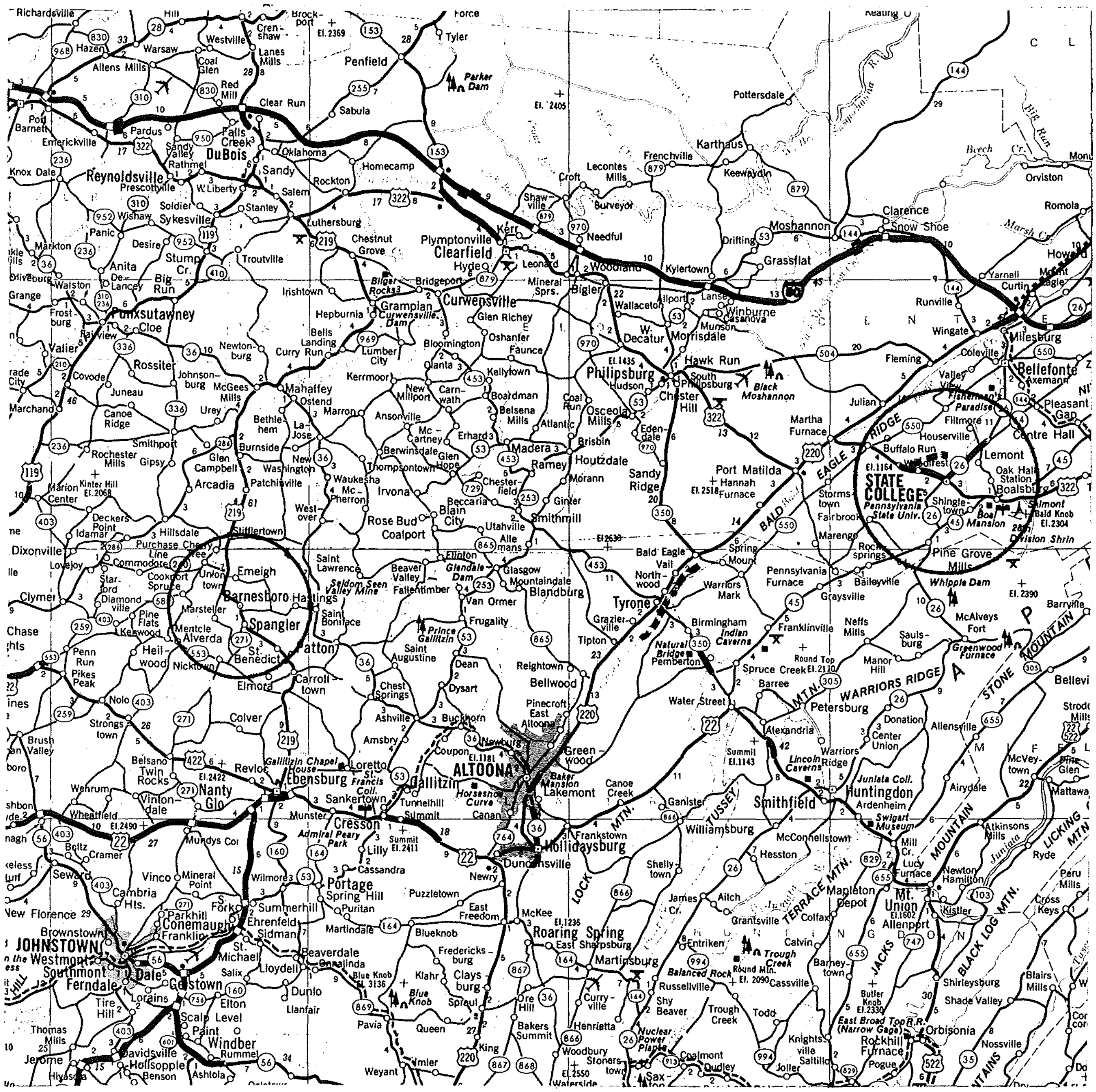

Figure 40 - Map Showing General Location of Greenwich Colliery, Barnesboro, Pa., With Respect to The Pennsylvania State University (State College, Pennsylvania)

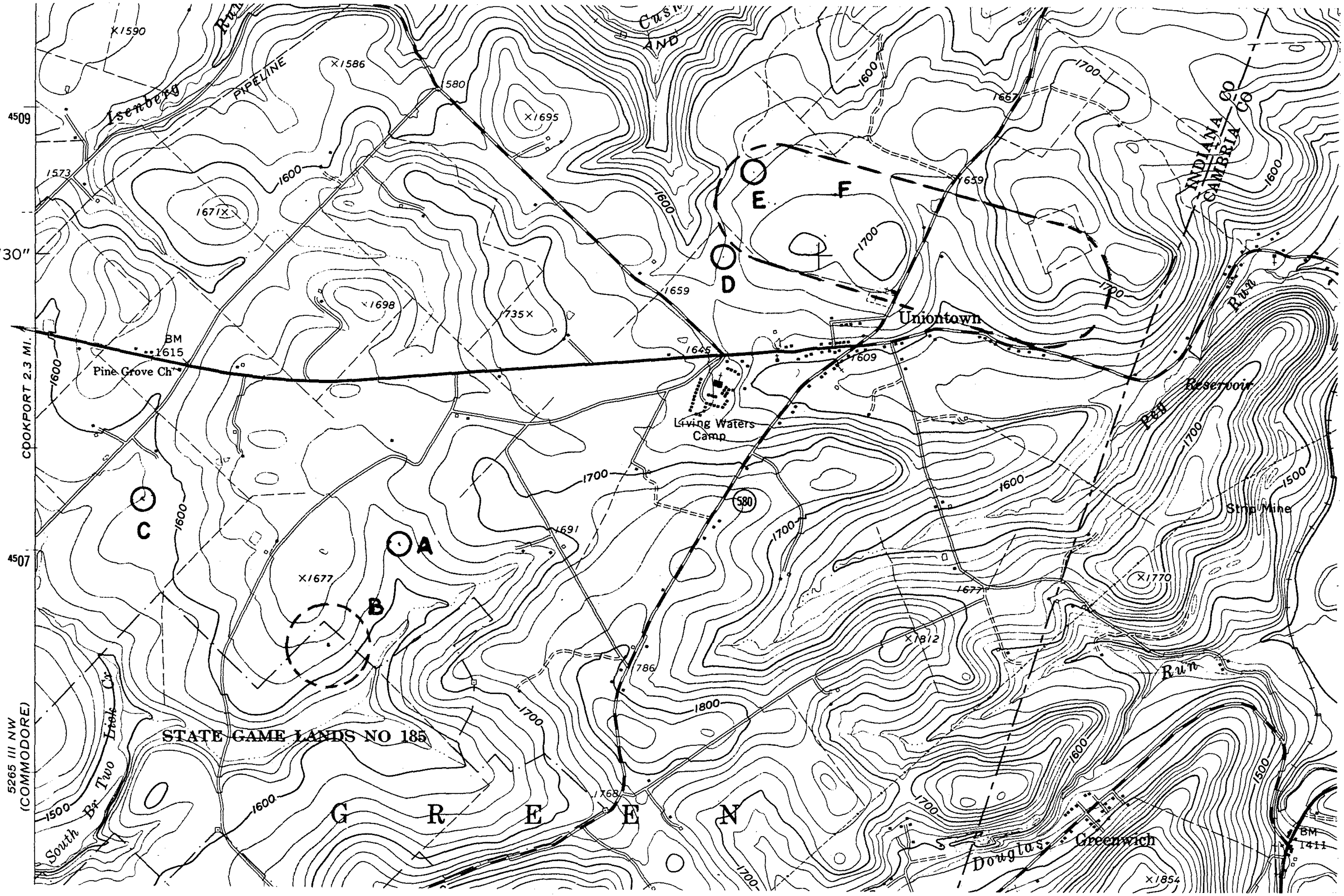

Figure 41 - Detailed Topographic Map of the Area Overlying the Greenwich Colliery, Barnesboro, Pa. [A & E - South and North Air Return Shafts, C & D - South and North Air Intake Shafts, B & F - Proposed South and North Microseismic Study Areas]

<u>Structure</u>: The structural relief between anticlines and synclines in the area is approximately 500-700 feet. The mine dips to the northwest (3.5%) down a syncline which has a slightly plunging axes in the northeast direction. This is typical of all folds in the areal trend, although the axis of the major synclinal basin underlying the Plateau plunges to the southwest (according to Fettke [43], p. 6), through Pittsburgh and the southwestern corner of the state.

<u>Stratigraphy</u>: The Appalachian Plateau is underlain by Devonian, Mississippian, Pennsylvanian, and Permain beds, cropping out in that order southward across the state. The majority of the Plateau in the State is underlain by the Pennsylvanian which has been divided into the Pottsville, Allegheny, Conemaugh, and Monongahela series (see Moore [44], p. 283).

An important characteristic of Pennsylvanian sedimentations are their cyclic nature. The Pennsylvanian cyclothem described by Weller [45] consists of a fairly constant lithologic or sedimentary sequence that is repeated many times throughout the stratigraphic column. The typical cycle in the Allegheny series of this area consists of the following sequence in ascending order: coal; black carbonaceous shale; sandy, dark gray to olive-drab, micaceous shale; sandstone grading upwards into siltstone; light to medium gray clay; dark gray, aphanitic, nodular limestone; and finally, plastic, light gray to brown, massive clay.

Jones [46] has reviewed the local stratigraphy with the aid of information from boreholes drilled earlier in the area of the Greenwich Mine (south mine). He found the strata to consist of "alternating and laterally discontinuous shales, siltstones, sandstones, and coal." From a mechanical point of view, the strata overlying the coal seam would therefore appear to be extremely complex, heterogeneous, and probably highly anisotropic.

1.3 Microseismic Study Areas

The Greenwich Colliery consists of two areas, designated as the North and the South mine. Figure 41 shows the location of the north and south shafts (D & E and A & C), as well as two proposed microseismic study areas (F & B). Initially, arrangements were made (during 1971) to carry out microseismic studies over a longwall panel at the south mine study area (B). During the late Spring of 1972, prior to installation of the first microseismic transducers at that location, it was found that mining operations there had been delayed by bad roof and floor conditions in the development areas. At that time, it appeared unlikely that longwall operations in the south mine would start before late 1972. It was, therefore, decided in the Summer of 1972 to shift microseismic studies at Greenwich to the north mine study area (F).

A number of microseismic test sites were utilized at the north mine. Approximate locations of these are shown in Figure 42. Later in this chapter, preliminary results of the microseismic studies carried out at each test site are presented along with a detailed description of each individual test site.

Initial microseismic studies were made at the air return site during Fall 1972 and Winter 1973 using shallow burial geophones. Studies at the A-2 site were carried out in Spring 1973 using surface mounted geophones as well as studies at the I(A) and I(C) B-4 sites using shallow burial geophones. In the Spring and Summer 1973, studies were undertaken at the I(B) B-4 site using both shallow and deep burial geophones as well as additional studies at the air return site using the borehole probe and both shallow and deep burial geophones. The I(D) B-4 site was instrumented with an array of deep burial geophones in the early Fall 1973. Tests at this site will continue through the Spring 1974 and are the subject of a new USBM project [G0144013] initiated in October 1973.

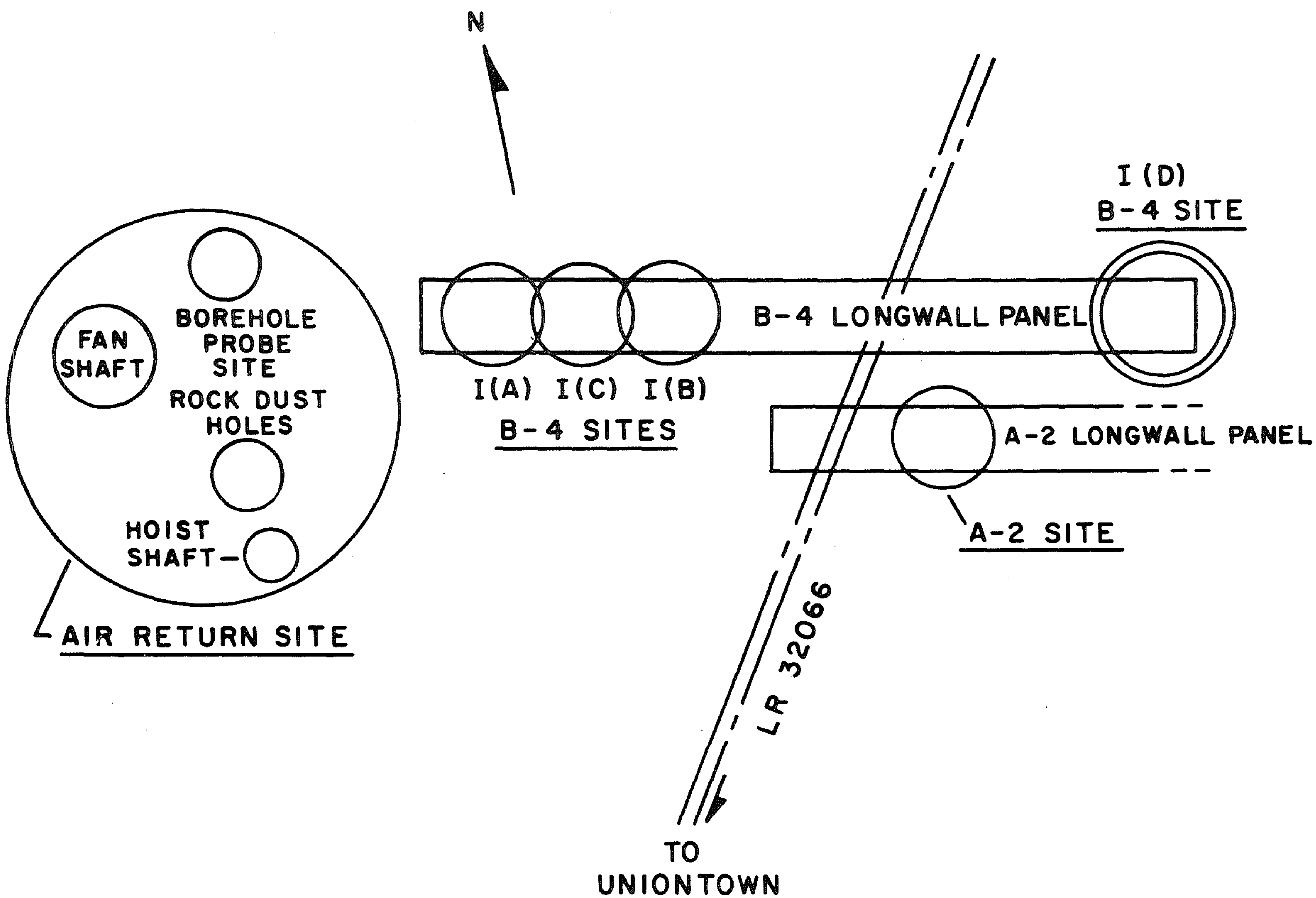

Figure 42 - Approximate Locations of Microseismic Test Sites at Greenwich North Mine Study Area

Measurements of field velocity were also undertaken at a number of locations at the Greenwich north mine study area. During the current project, such velocity measurements were made at the I(B) and I(C) locations on the B-4 longwall. Later studies have been made at the air return site (borehole probe and rock dust hole locations). Appendix H outlines briefly the field velocity studies, however, a detailed review of these studies, which are still underway, will be delayed for presentation in the final report for project G0144013 scheduled for completion towards the end of 1974.

2. <u>General Field Procedures</u>

Travel time from the project base at State College, Pa. to the Greenwich field site, located near Barnesboro, Pa., was approximately three hours. It was therefore possible to carryout the majority of the field trips on a daily basis returning to State College at night. During longer term field studies key personnel remained near the field site overnight, usually at Ebensburg, Pa. some 20 miles south of Barnesboro.

Where possible, specific field trips were usually scheduled a month in advance. All project staff met formally at least once a month to discuss progress, consider problems and plan for future field trips. Considerable difficulties were found to arise in using graduate students on field oriented aspects of the project due to their lecture schedule. This problem was overcome by shifting the major field assignments to full time research associates and utilizing graduate students on less critical field studies, the timing of which could be adjusted to their lecture schedule.

For single day field trips the personnel usually assembled at the University at 7:00 A.M. and left for the field site between 7:00-7:30 A.M. Transportation was provided by University fleet vehicles or in some cases personal automobiles. In those cases where the mobile microseismic monitoring facility was utilized it was necessary to also have at least one other vehicle along to provide local transportation at the field site.

On arrival at the field site the mobile monitoring facility and associated trailer were unpacked. One group of personnel ran-out the cables to the desired transducer locations and connected up the various preamplifiers, junction boxes, etc. The other group set up the motor generator power supply and prepared the monitoring system for operation. Where possible the monitoring system was "warmed-up" for about 1/2-hour prior to recording of field data.

During studies associated with the west B-4 longwall, when possible, one of the project personnel was located underground in the longwall face area during at least a portion of the time that surface microseismic monitoring was underway. His function was to keep an accurate log of all underground activities (support advance, roof fracture, problems, etc.) as a function of time so that these could later be correlated with recorded microseismic activity. The use of an underground observer has become routine procedure in recent longwall studies (project G0144013 presently underway). Here the observer normally goes underground during the second shift (3:30 P.M.) and remains there for 3-4 hours during which microseismic surface monitoring is underway.

Surface measurements were usually terminated approximately one hour prior to dark to provide sufficient time for collection and packing of equipment. In those cases where a series of field trips to the same test site were underway the transducer cables were usually left in place ready for the next monitoring session. Following completion of the days field study the project staff returned to the project base, usually by 10:30-11:00 P.M.

When the field studies required measurements over a series of adjacent days, the monitoring system was left at the field site overnight ready for next day, and personnel returned to local accommodation (Ebensburg, Pa.) for the night.

3. Preliminary Results

As mentioned earlier the major purpose of this project has been the development of a mobile monitoring facility and associated field techniques for the study of microseismic activity in coal mines using a surface mounted transducer array. A detailed description of results obtained in a number of microseismic study areas at the Greenwich mine site (see Figure 42) will be presented in a later report however for completeness a brief preliminary outline of these results will be included here.

3.2 Air Return Site

The initial microseismic study area at the north mine was the air return site (see Figure 42). This site is shown in detail in Figure 43. It was felt that this would be an excellent area in which to conduct initial studies since the surface area here was owned by the Greenwich Company, furthermore the area was generally flat and contained a large number of logging roads providing excellent access. Development work in this area had been troubled by a considerable number of large roof failures which it was felt could provide an interesting phenomena to investigate microseismically, and hopefully, results would be directly useful to the company. At that time the longwall panels in the north mine were expected to start operating late in 1972 or early in 1973, and by that time it was felt that considerable field experience should have been obtained in this area.

Roof falls at the air return site range from 7 to 20 feet in height, and some appear possibly to be higher. Once a roof fall starts, it has a tendency to run until stopped. Furthermore, no definite pattern appears to be evident, and roof fall zones meander at will along entries and through cross cuts until entries have to be completely cribbed in order to stop them. According to Yonkoske [42], the primary cause for the roof falls may be

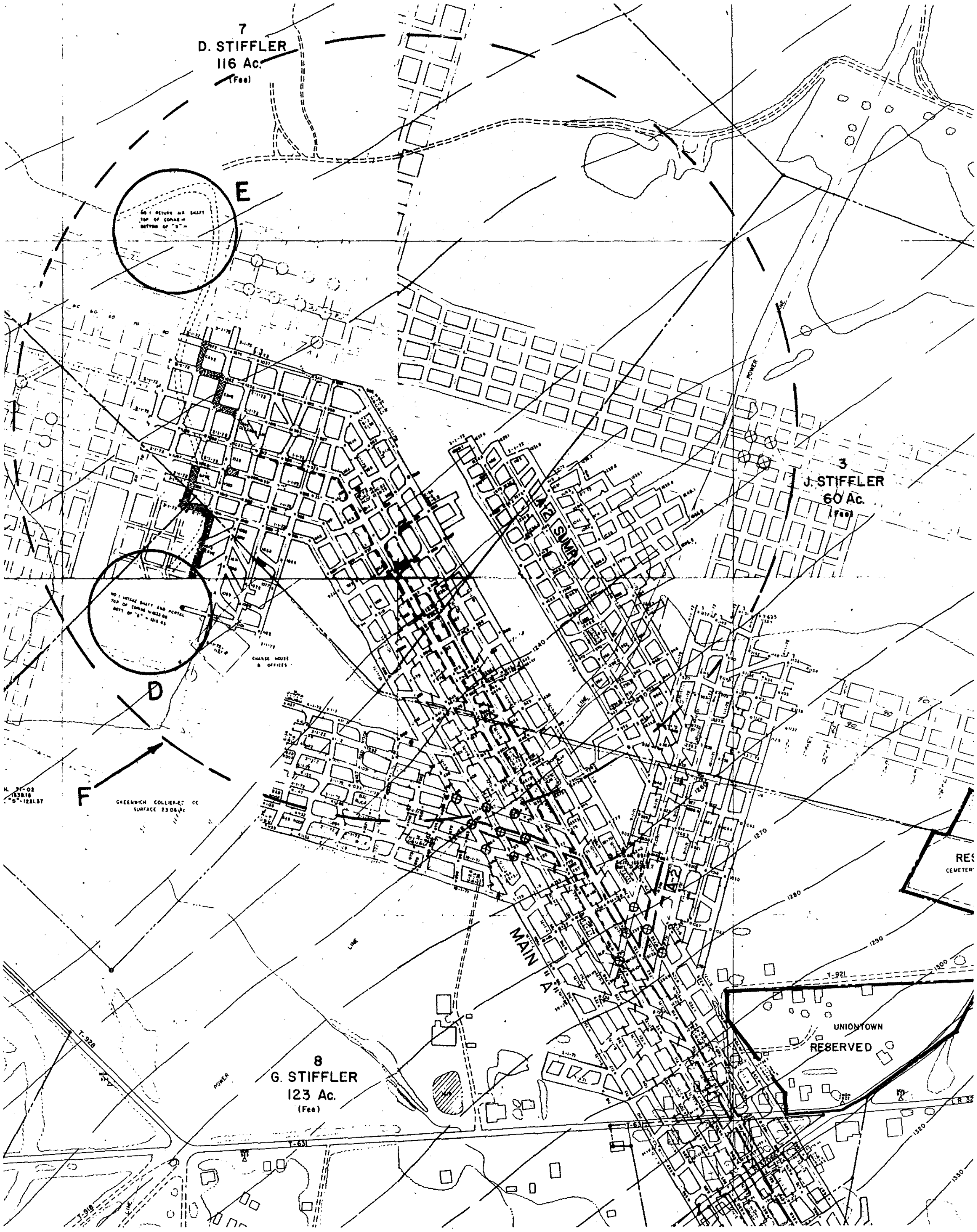

Figure 43 - Map of Section of North Mine, Greenwich Mine, Barnesboro, Pa., Showing Air Return Shaft Site (F)
[D - Intake Air Shaft and Portal, E - Air Return Shaft]

attributed to fractures and joints in the overlying strata. Clay veins extend beyond the height of roof falls and in all directions. These are a major source of weakness. Cracks containing coal and argillaceous silty deposits can be traced as high as 3 feet above the coal seam.

On November 2, 1972, a shallow-burial geophone array was installed at the air return site. Figure 44 shows the approximate location of various transducers at this test site. Those installed on November 2, 1972 are shown by solid dots (i.e. 1, 2, 3, 4, 5, 6, and 7). Appendix I gives detailed survey data for these transducer locations. 14 Hz geophones were installed following the standard procedure described earlier in this report. A suitable parking area was constructed by Greenwich mine personnel in the vicinity of transducer No. 1 (see Figure 44) for parking the monitoring facility during field studies.

Microseismic measurements were made at this site on November 8 and 29 using both battery and motor generator power. In most cases the system was operated with filters set 0-2500 Hz, and an overall system gain of 60 db (40 db preamp plus 20 db post amp). Considerable general background noise was noted along with randomly occurring large bursts of noise which were suspected of being due to operation of the hoist motor. On December 11 a single geophone (No. 9) was installed on surface close to the intake shaft (see Figure 44). On December 13 microseismic activity was again monitored at the air return site, and a radio link, between the hoist shaft and the monitoring facility, was utilized to provide information as to the times when the hoist motor was operating. In general the very large bursts of apparent microseismic activity observed on the microseismic records were found to be associated directly with hoist motor operation. Because these bursts occurred on all geophone channels simultaneously it became obvious that the signals were electromagnetically coupled into the monitoring system either through the geophones or the transducer cables.

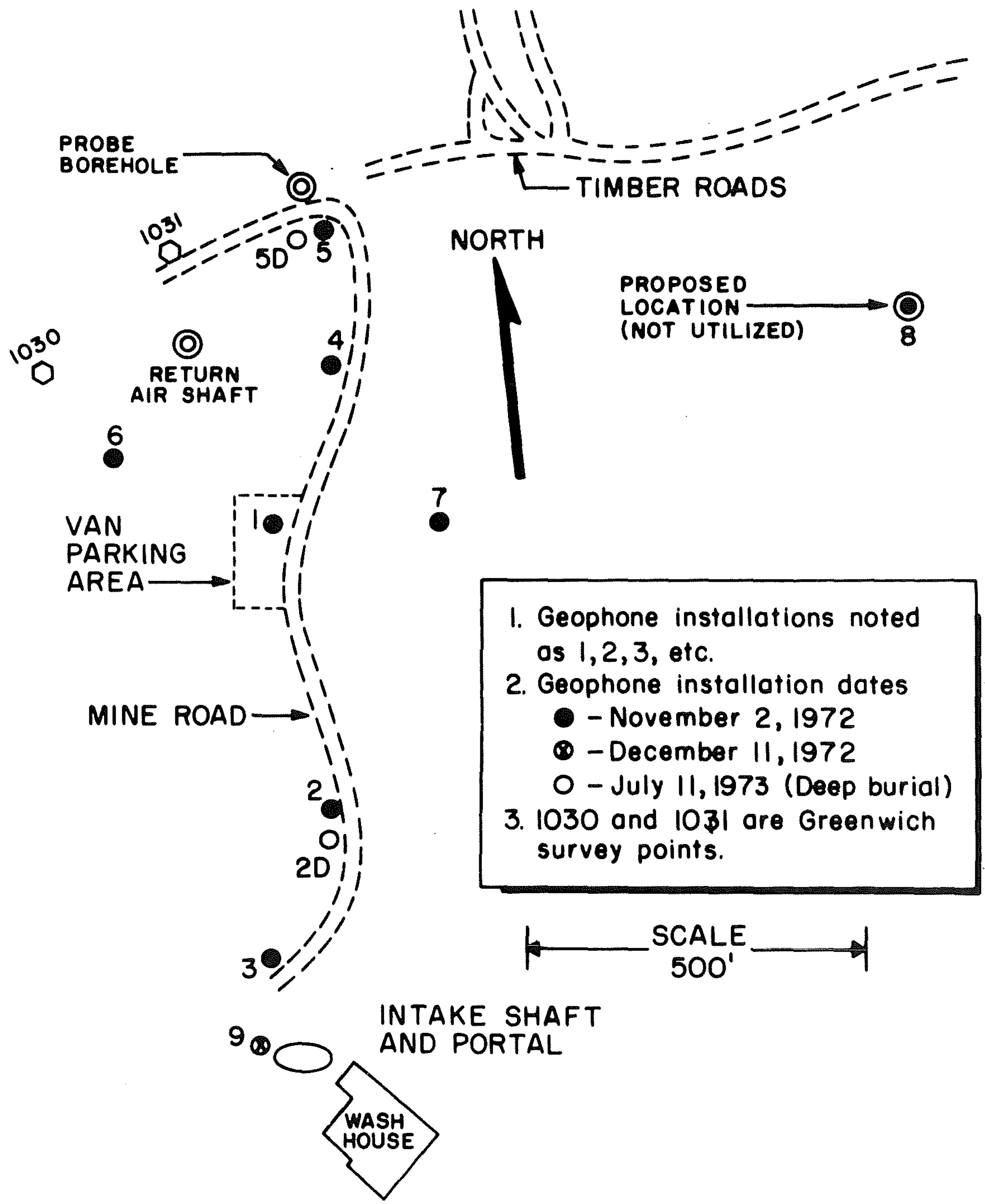

Figure 44 - Approximate Location of Various Transducers at Air Return Shaft Site [2D and 5D denote deep burial geophones]

A further series of tests were conducted at the air return site on March 26, 1973. Microseismic measurements were carried out for approximately 2 hours during which various geophone shunting resistors were utilized in an effort to reduce the effect of the hoist motor radiation. The use of lower value shunting resistors did appear to improve the situation, however only to a limited degree.

On June 26, 1973 a 139 foot deep probe borehole was drilled at the air return site (see Figure 44). As well on July 6 two 20 foot holes were augered down to bedrock at geophone locations No. 2 and 5. Two deep burial geophones (2D and 5D) were cemented into these holes at depths of 19 and 17 feet respectively. Microseismic activity was monitored using geophones 2D and 5D as well as a number of the shallow burial geophones for a 1-1/2 hour period on July 13. Figure 45 shows a section of typical background recorded using geophones 1, 2, 4, 5, 5D and 9. Figures 46 and 47 show sections of the same data expanded in time x 10 and x 100 respectively.

In all cases both recording and playback were carried out using filters set at 0-1000 Hz. With the filtering employed no obvious true microseismic events appear to be present in the data.

Figure 48 illustrates a burst of typical hoist noise monitored on July 13, 1973. Figure 49 illustrates the same burst expanded in time x 100. It should be noted that all geophone channels are effected simultaneously indicating that the disturbance was electromagnetic in form. Figure 50 illustrates a spike form of electromagnetic signal that was commonly detected at the air return site. Again it should be noted that the signal occurs on all channels simultaneously.

Microseismic activity was again measured at the air return site on November 9, 1973. This time signals from six geophones and the borehole probe

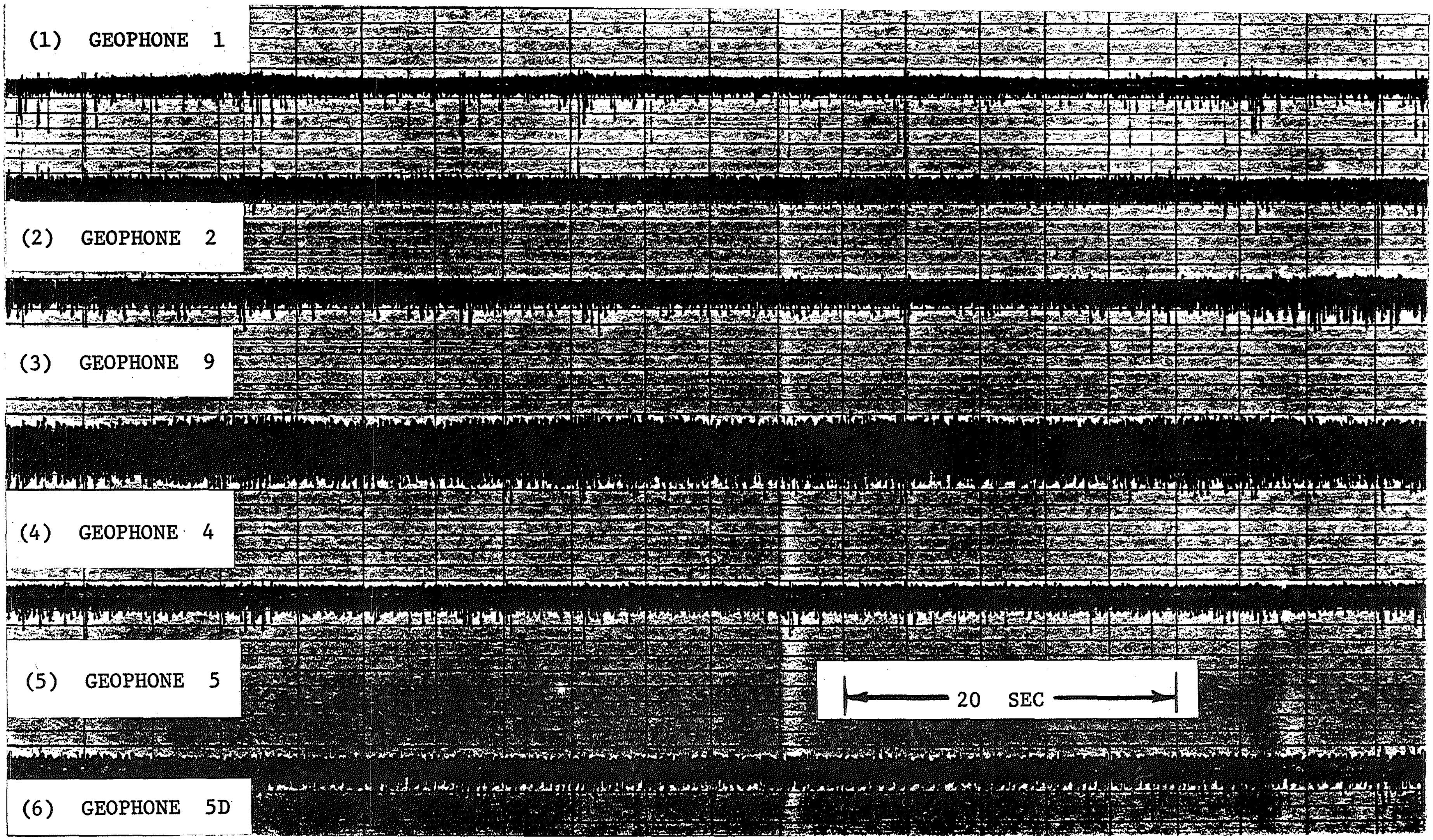

Figure 45 - Typical Microseismic Background Recorded at Air Return Site, July 13, 1973 - Slow Speed Playback
[Record/Playback Filters 0-1000 Hz, Tape Location 103-1160]

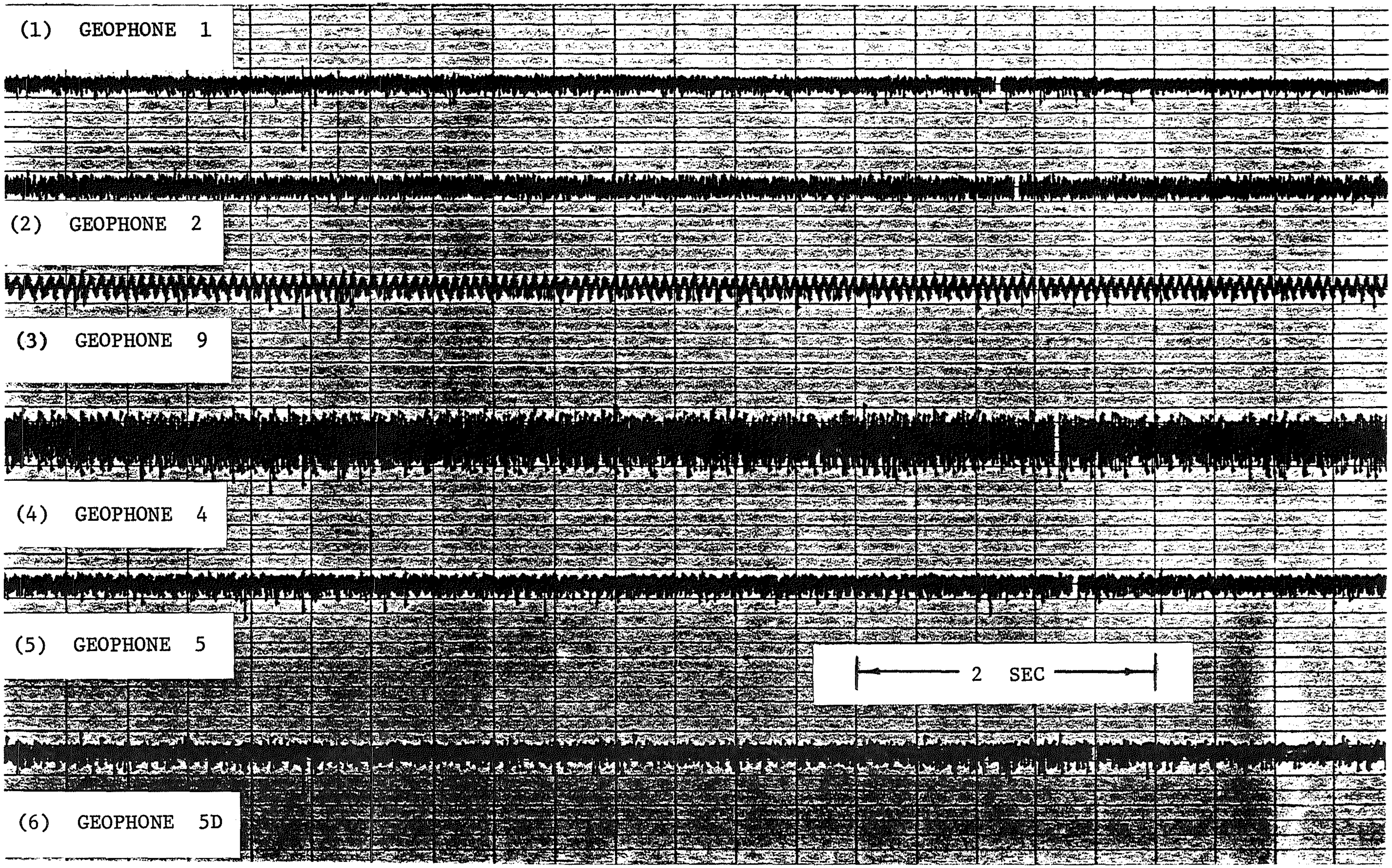

Figure 46 - Typical Microseismic Background Recorded at Air Return Site, July 13, 1973 - Medium Speed Playback [Record/Playback Filters 0-1000 Hz, Tape Location 103-1168]

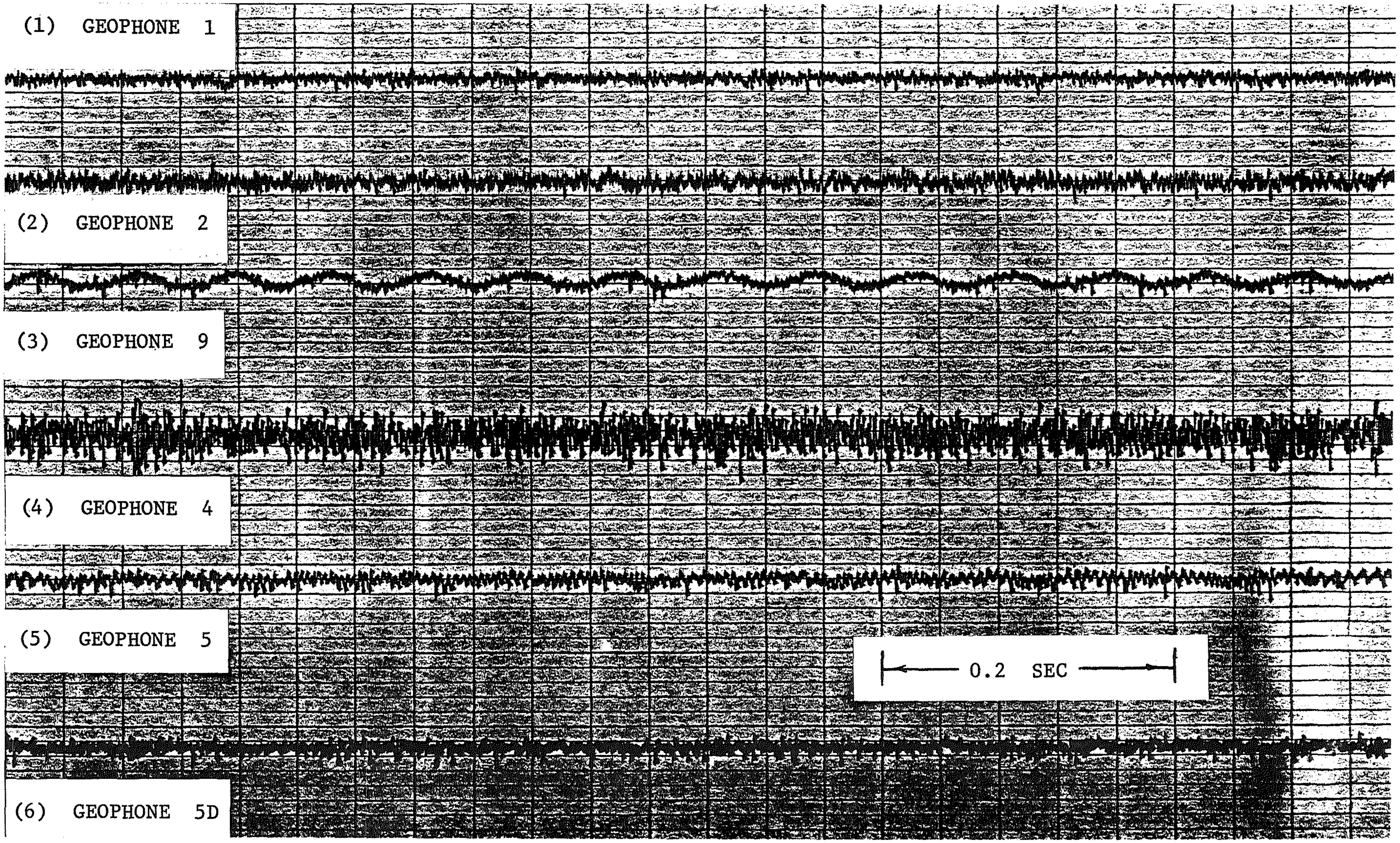

Figure 47 - Typical Microseismic Background Recorded at Air Return Site, July 13, 1973 - Fast Speed Playback [Record/Playback Filters 0-1000 Hz, Tape Location 103-1168]

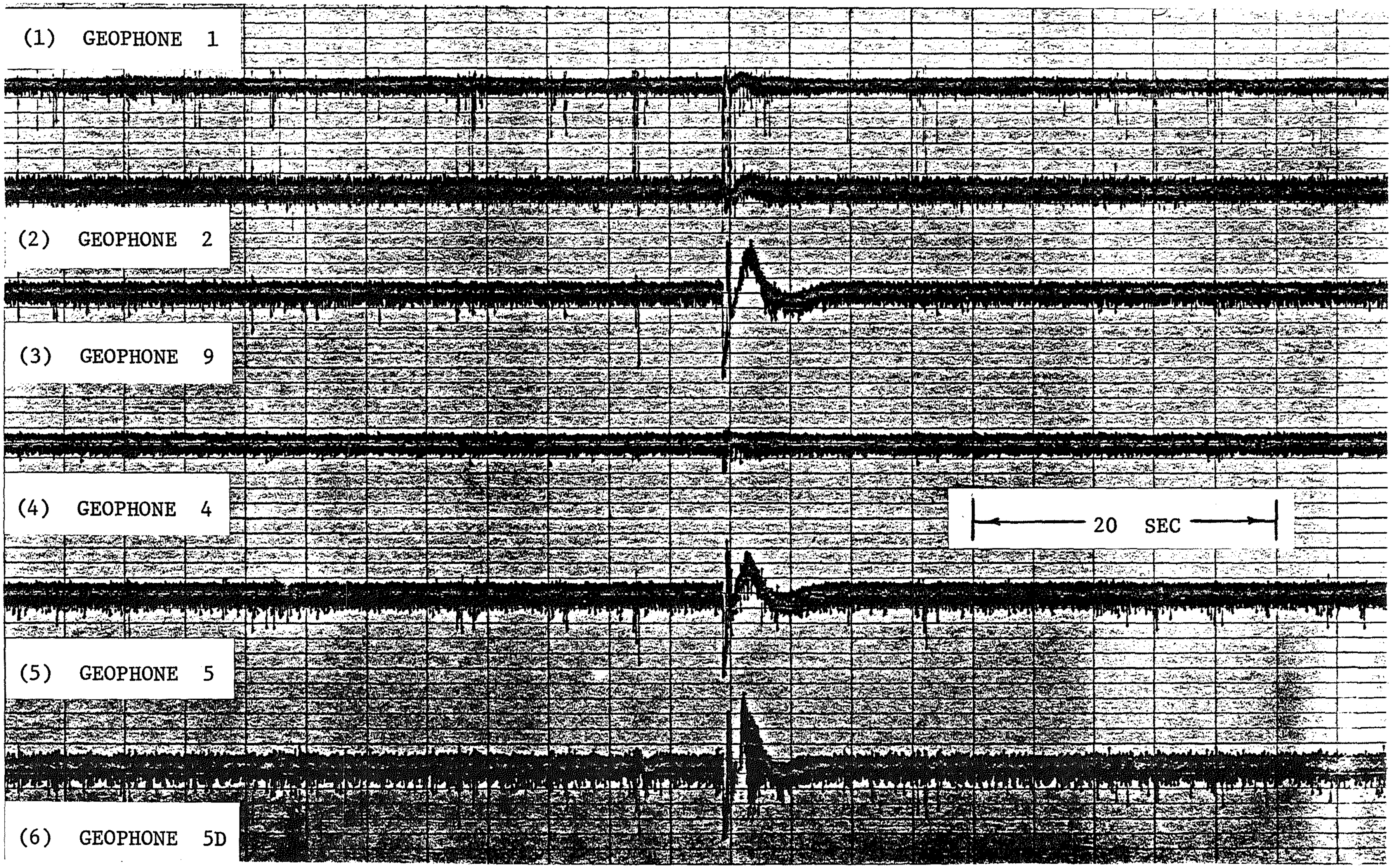

Figure 48 - Burst of Typical Noise Associated with Hoist Operation at Air Return Site, July 13, 1973 - Slow Speed Playback [Record/Playback Filters 0-1000 Hz, Tape Location 103-1271]

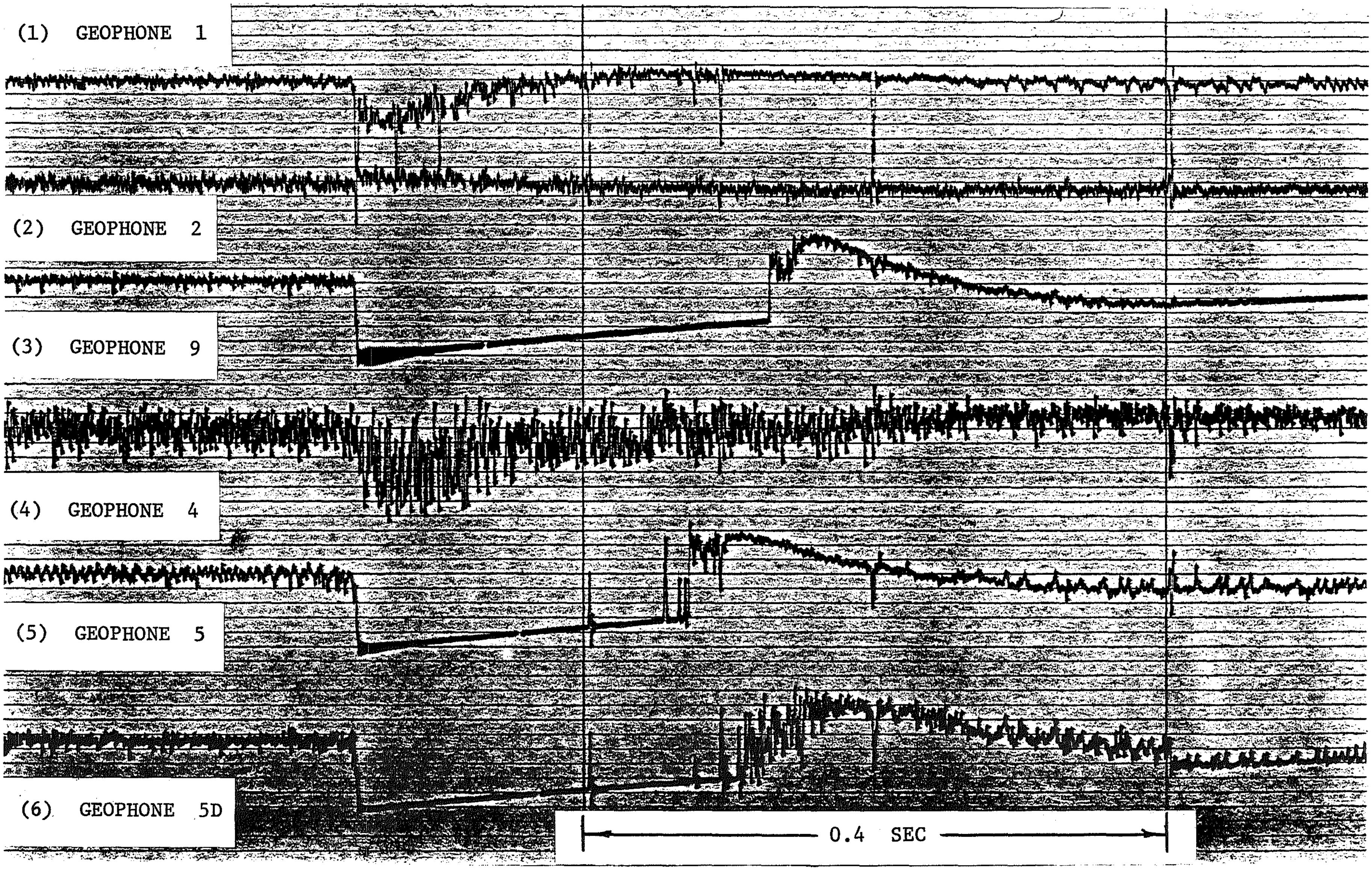

Figure 49 - Burst of Typical Noise Associated with Hoist Operation at Air Return Site, July 13, 1973 - Fast Speed Playback [Record/Playback Filters 0-1000 Hz, Tape Location 103-1281]

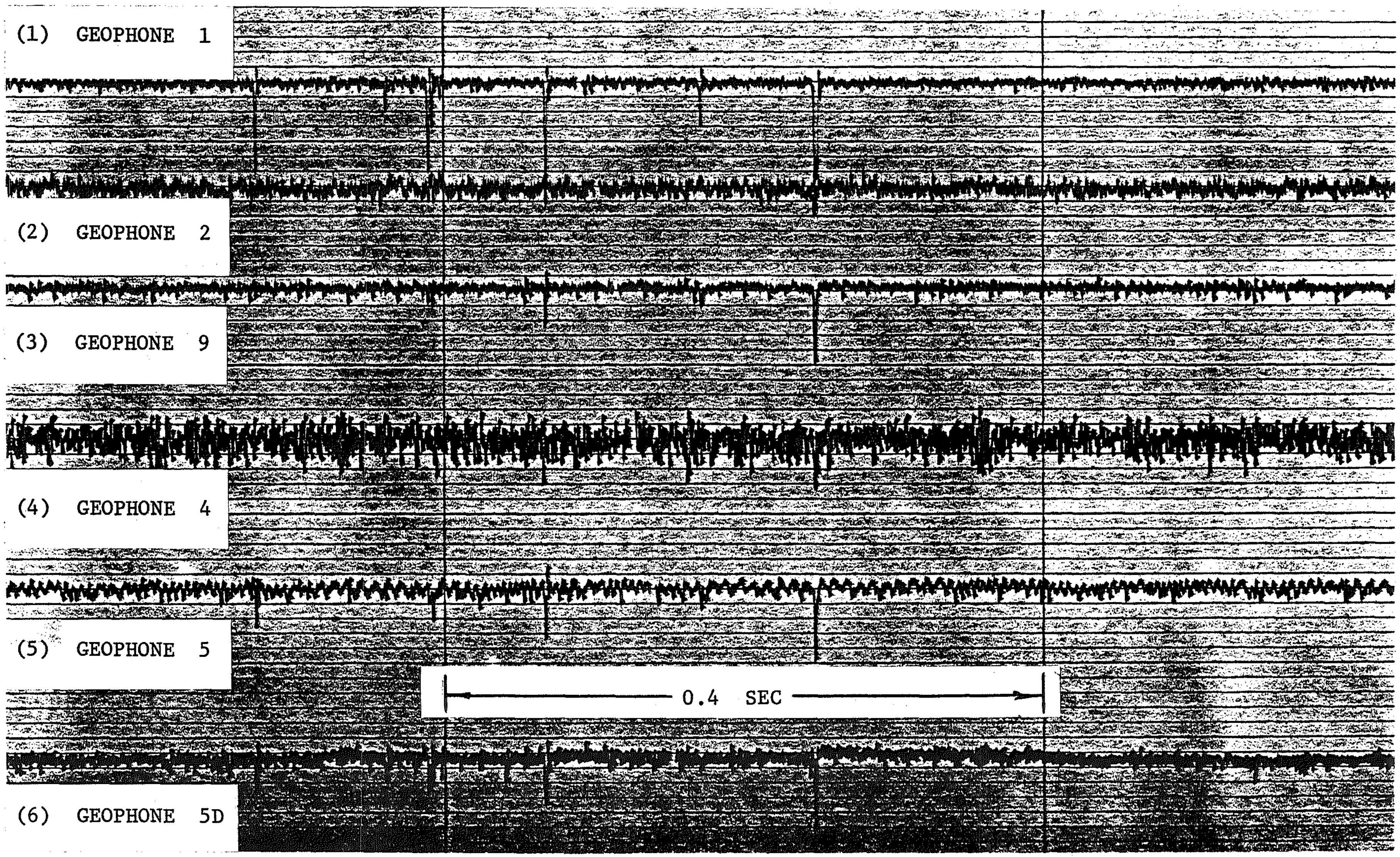

Figure 50 - Typical Noise Spikes Observed at Air Return Site, July 13, 1973 - Fast Speed Playback [Record/Playback Filters 0-1000 Hz, Tape Location 103-1281]

were monitored. It should be noted that this was the first set of measurements made at this site using transducer junction boxes containing filters (see Figures 35 & 36). Figure 51 shows a section of typical microseismic background including what appears to be a characteristic noise burst due to the hoist. Figure 52 shows a section of the same data expanded in time x 100 as well as amplified 12 db. Again as with the data observed on July 13 there appears to be no true microseismic events present; at least none are evident with the filtering utilized. The absence on the November 9 data of the large number of high frequency spikes noted in the July 13 data is probably due to the presence of the junction box filter utilized in the latter tests.

Figure 53 illustrates a typical hoist noise observed on November 9. In general it is similar in form to those observed earlier (see Figure 48) but with less high frequency character due to the presence of the filter junction boxes in the system.

3.2 A-2 Longwall Site

The first opportunity to monitor microseismic activity associated with longwall mining at the Greenwich mine was at the A-2 site (see Figure 42). Figure 54 shows a portion of the mine plan containing the A-2 longwall. Figure 55 shows the longwall position at the time of the measurements and the approximate location of the geophones and the monitoring facility. At that time the longwall operation was reported to be progressing favorably with advances of up to 60 feet per day and good roof caving conditions behind the longwall.

On February 14, 1973 microseismic measurements were made at the A-2 site. Due to the heavy forest cover in the test area it was only possible to set up a simple linear array of surface mounted geophones as shown in Figure 55. Distances presented are only approximate since no accurate survey was carried out at this site. Data was recorded over a two hour period during which poor

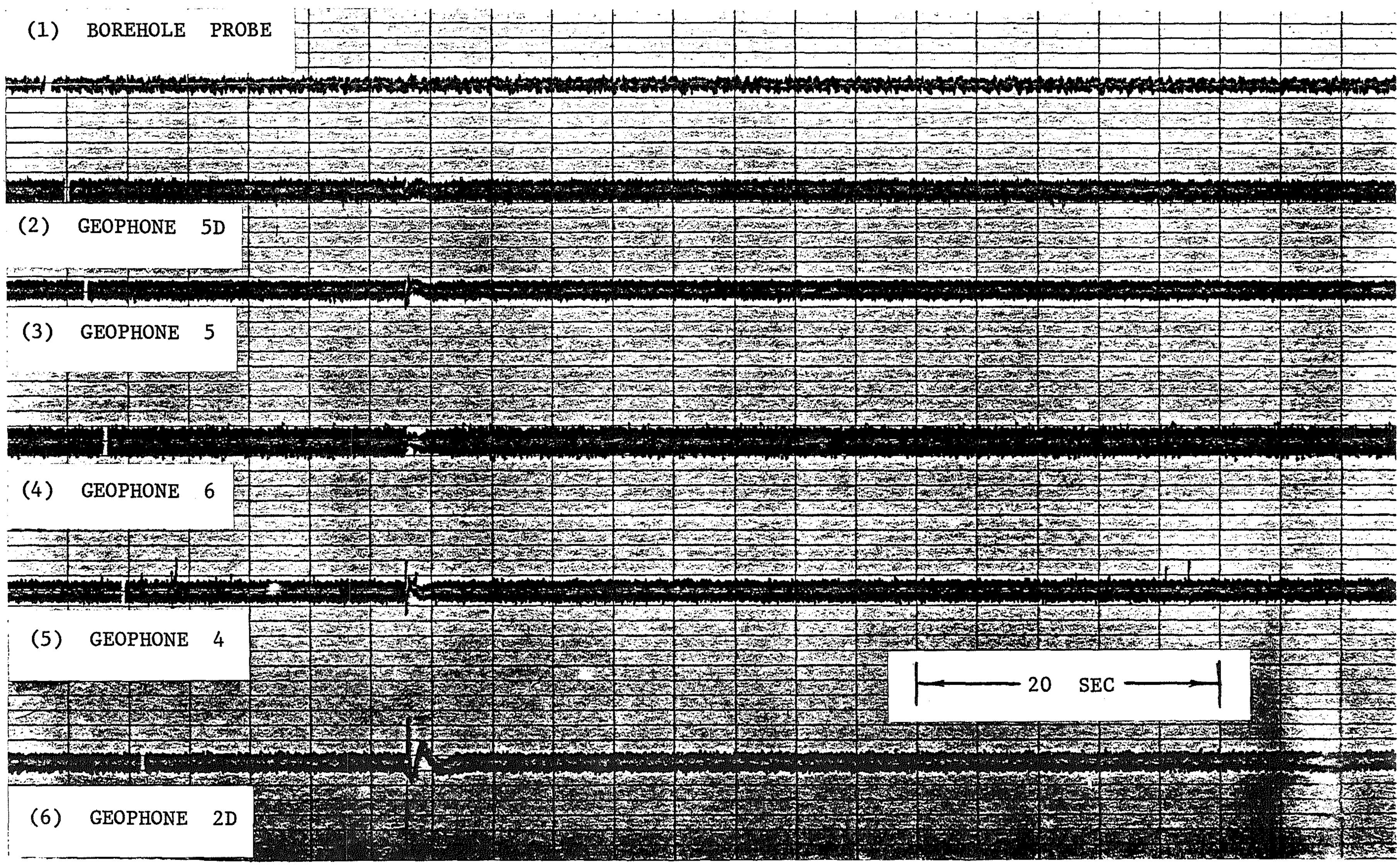

Figure 51 - Typical Microseismic Background Recorded at Air Return Site, November 9, 1973 - Slow Speed Playback (Note presence of a hoist disturbance at A) [Record/Playback Filters 0-1000 Hz, Tape Location 103-2320]

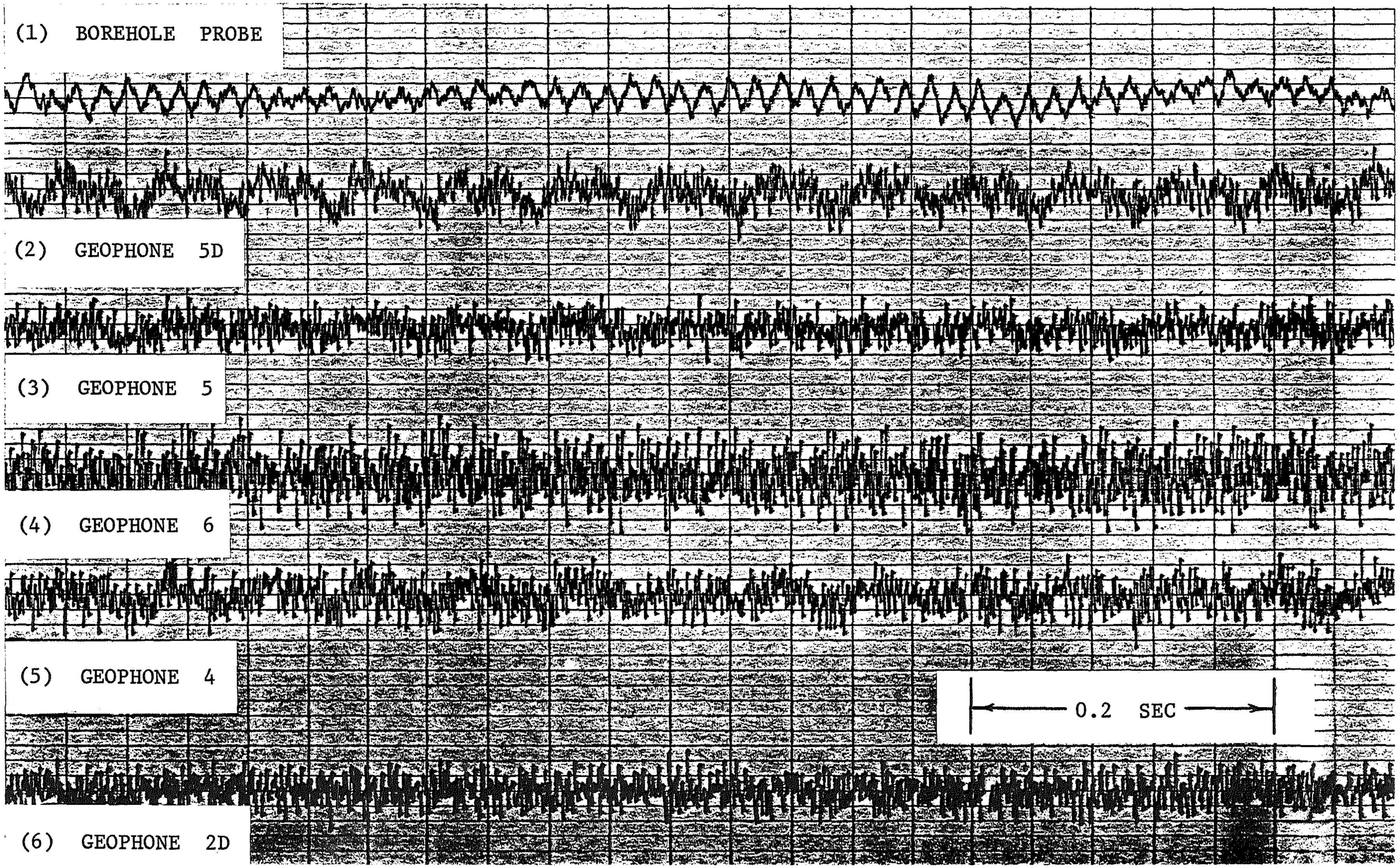

Figure 52 - Typical Microseismic Background Recorded at Air Return Site, November 19, 1973 - High Speed Playback [Record/Playback Filters 0-1000 Hz, Tape Location 103-2327]

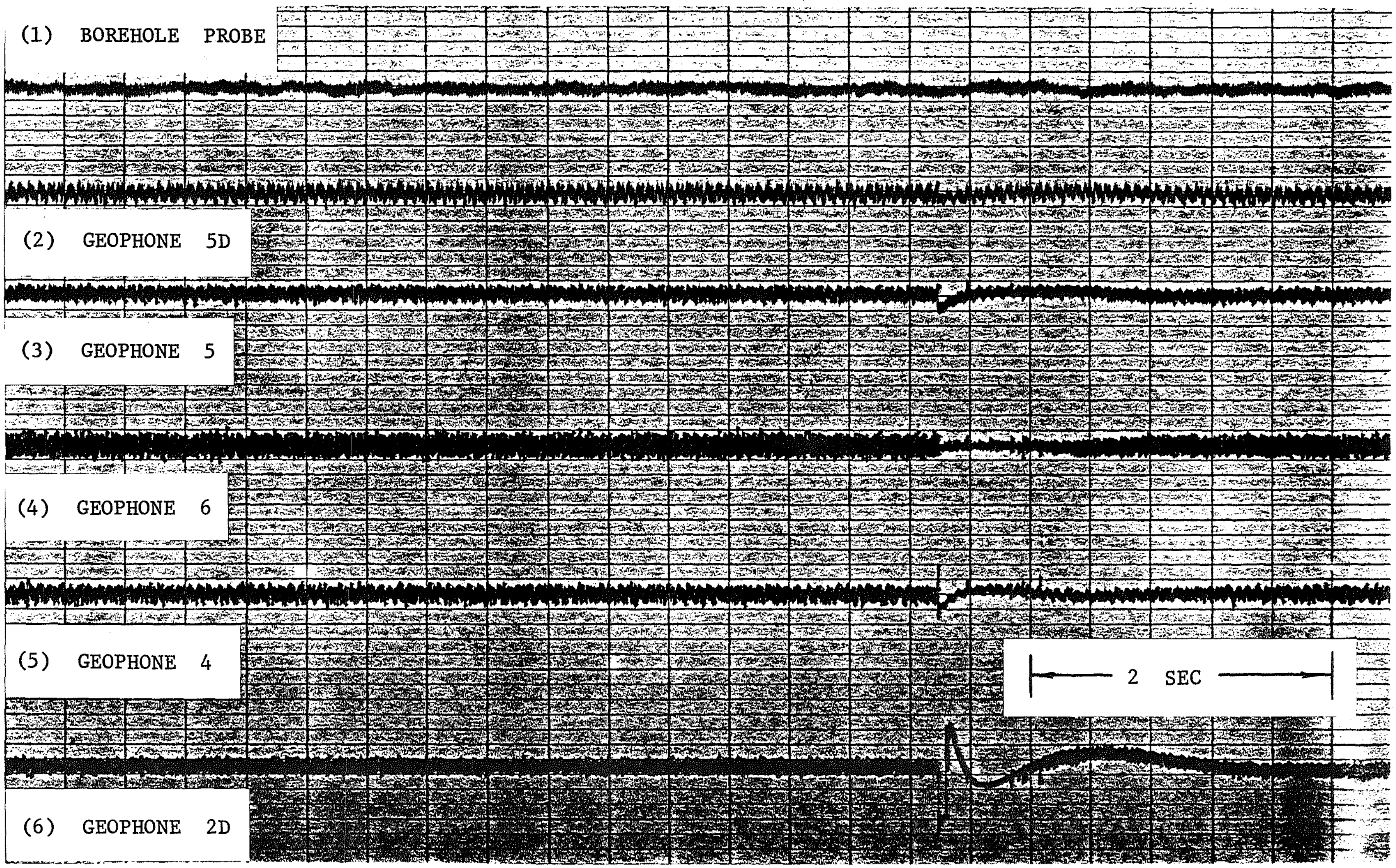

Figure 53 - Burst of Typical Noise Associated with Hoist Operation at Air Return Site, November 9, 1973 - Medium Speed Playback [Record/Playback Filters 0-1000 Hz, Tape Location 103-2322]

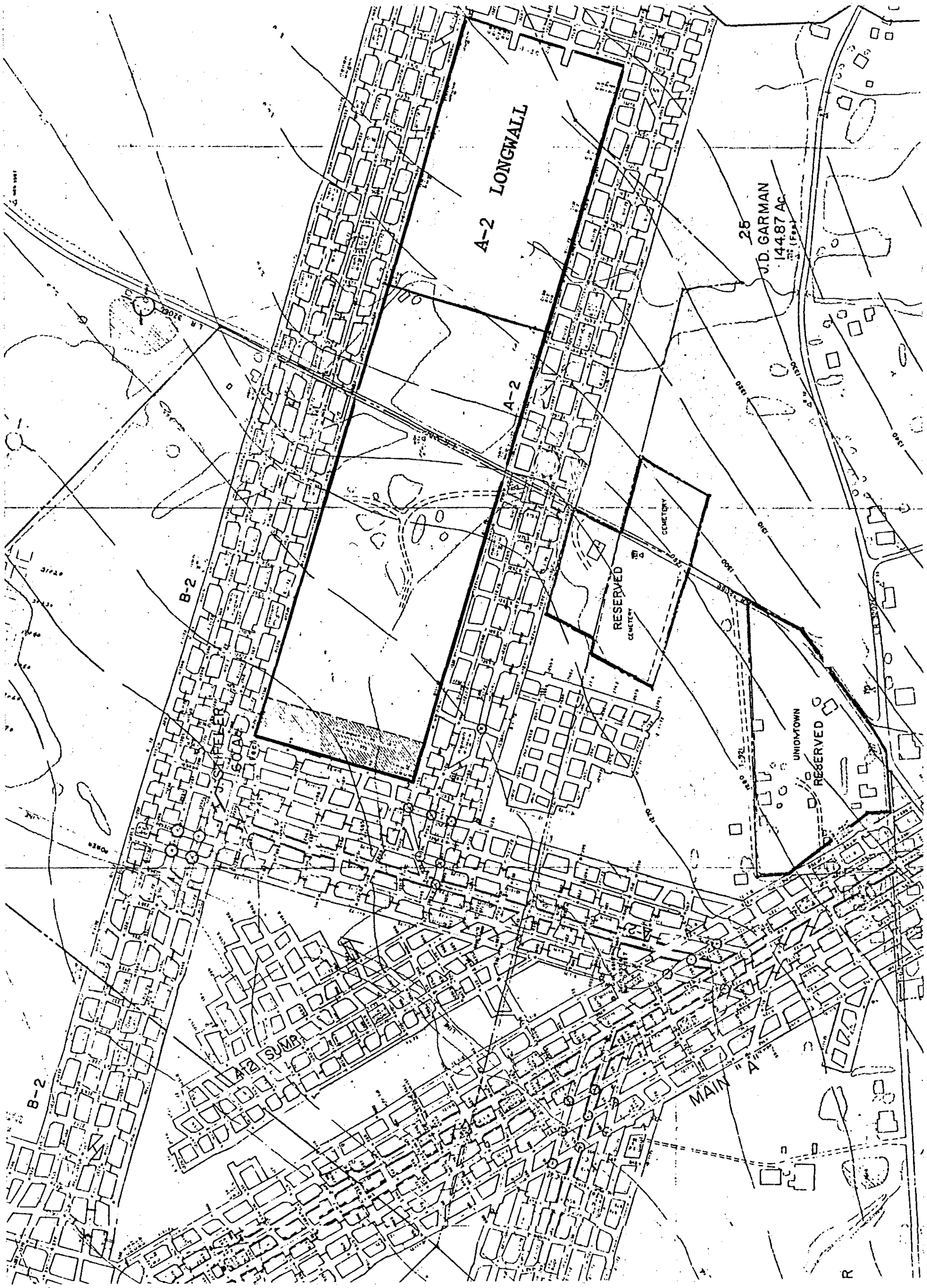

Figure 54 - Section of Greenwich Mine Plan Including A-2 Longwall Site

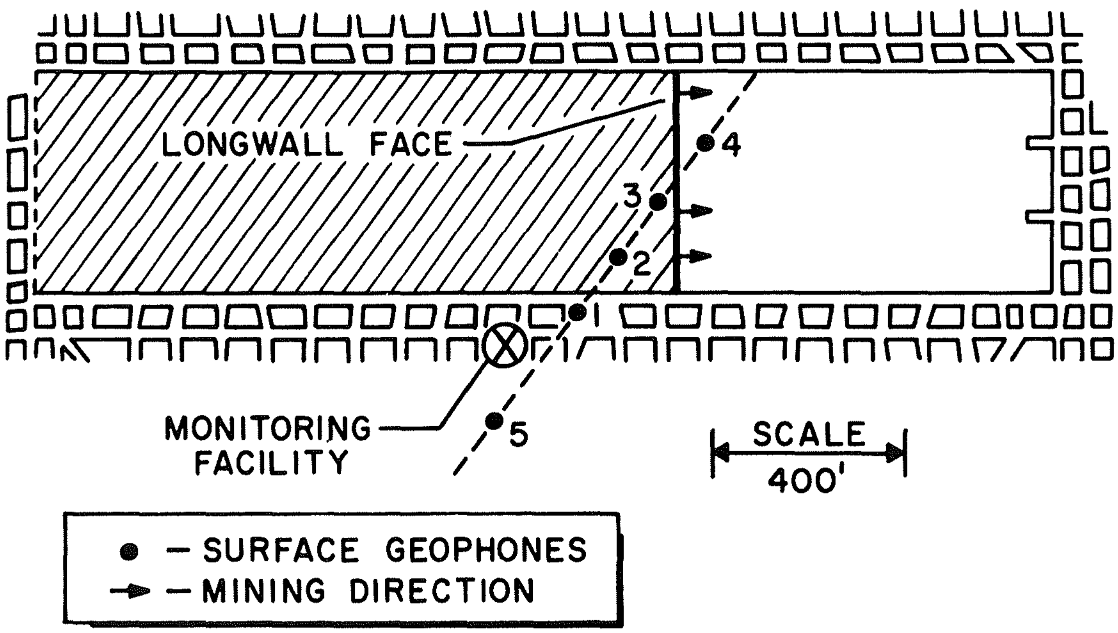

Figure 55 - Details of A-2 Longwall Site Showing Position of Longwall Face and Geophone Locations

weather conditions were experienced including rain alternating with freezing rain and sleet. An effort was made to protect the surface mounted geophones from the weather by covering them with cardboard boxes. In spite of the experimental difficulties a large number of microseismic like signals were observed during monitoring. In many cases these signals were 2-8 times the general background level.

Figure 56 illustrates microseismic data detected by the five transducers during a selected 60 second period. It is interesting to note that transducers 2 and 3 are directly over the area being mined and exhibit maximum activity; transducer 4 is over the unmined area (solid coal); transducer 1 is over the edge of the mining area, and transducer 5 is approximately 300 feet from the mining area (over a development area mined considerably earlier) and exhibits minimum activity.

During these measurements, filter limits in the monitoring system were set at 0-2500 Hz. Figure 57 illustrates a number of typical microseismic signals detected during the two-hour monitoring period. In Figure 57A the near coincidence of events, M, N and O indicate that they are a result of the same underground instability. Figure 57B shows the same events with data played-back at a slower tape speed in order to display the detailed character of the signals. Figures 47C, D and E illustrate a number of other typical microseismic signals observed during the study.

A simple frequency analysis study (as described earlier under "Data Analysis Procedures") was carried out on a number of microseismic signals and on sections of typical background. Figure 58 shows the frequency spectra for two microseismic signals, and Figure 59 shows the comparison between the spectrum of a microseismic signal and background. It is apparent that the background covers a wide frequency range, in contrast however typical

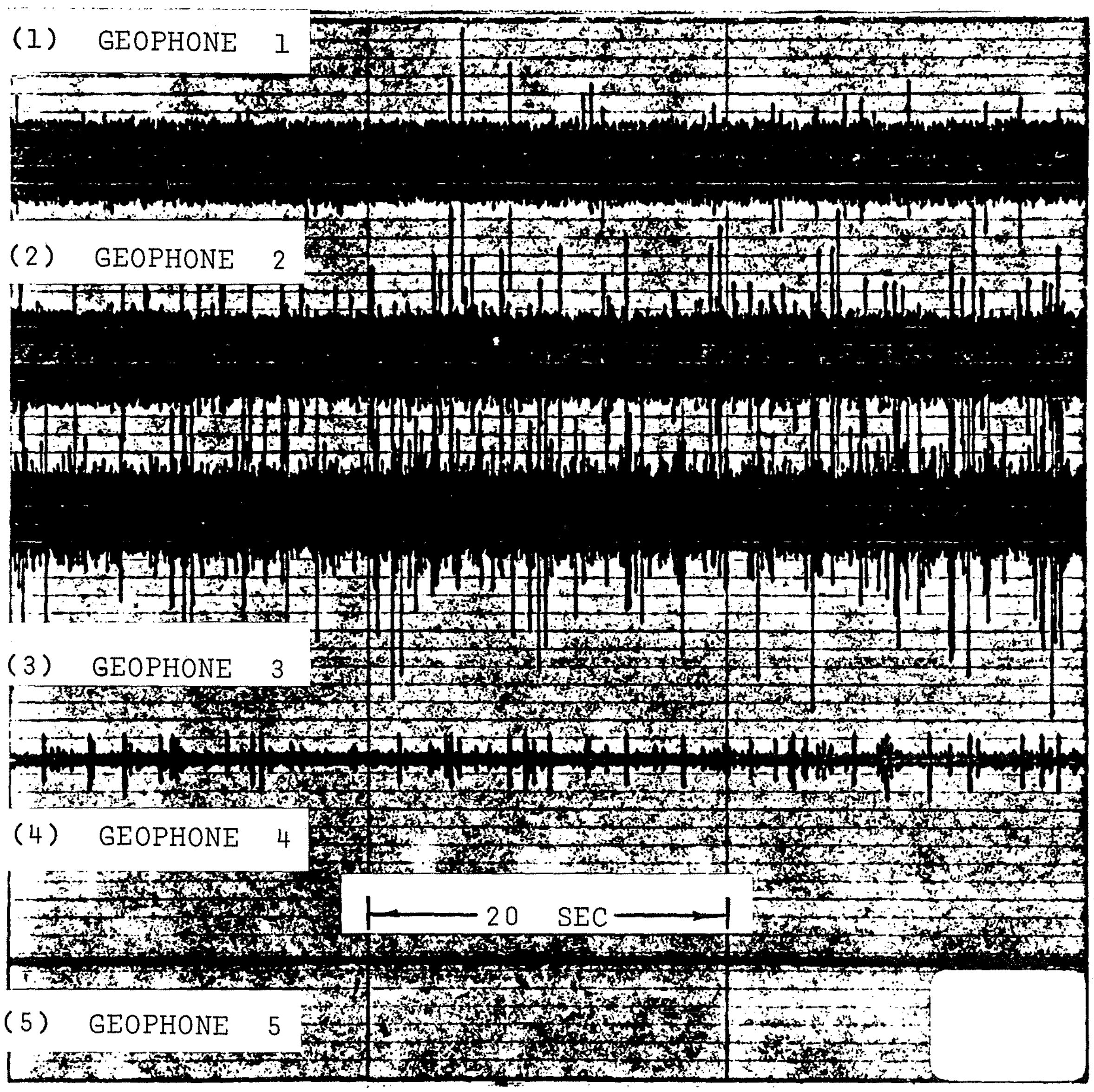

Figure 56 - Microseismic Signals Detected During a 60 Second Test Period at the A-2 Longwall Site, February 14, 1973 - Slow Speed Playback [Record/Playback Filters 0-2500 Hz]

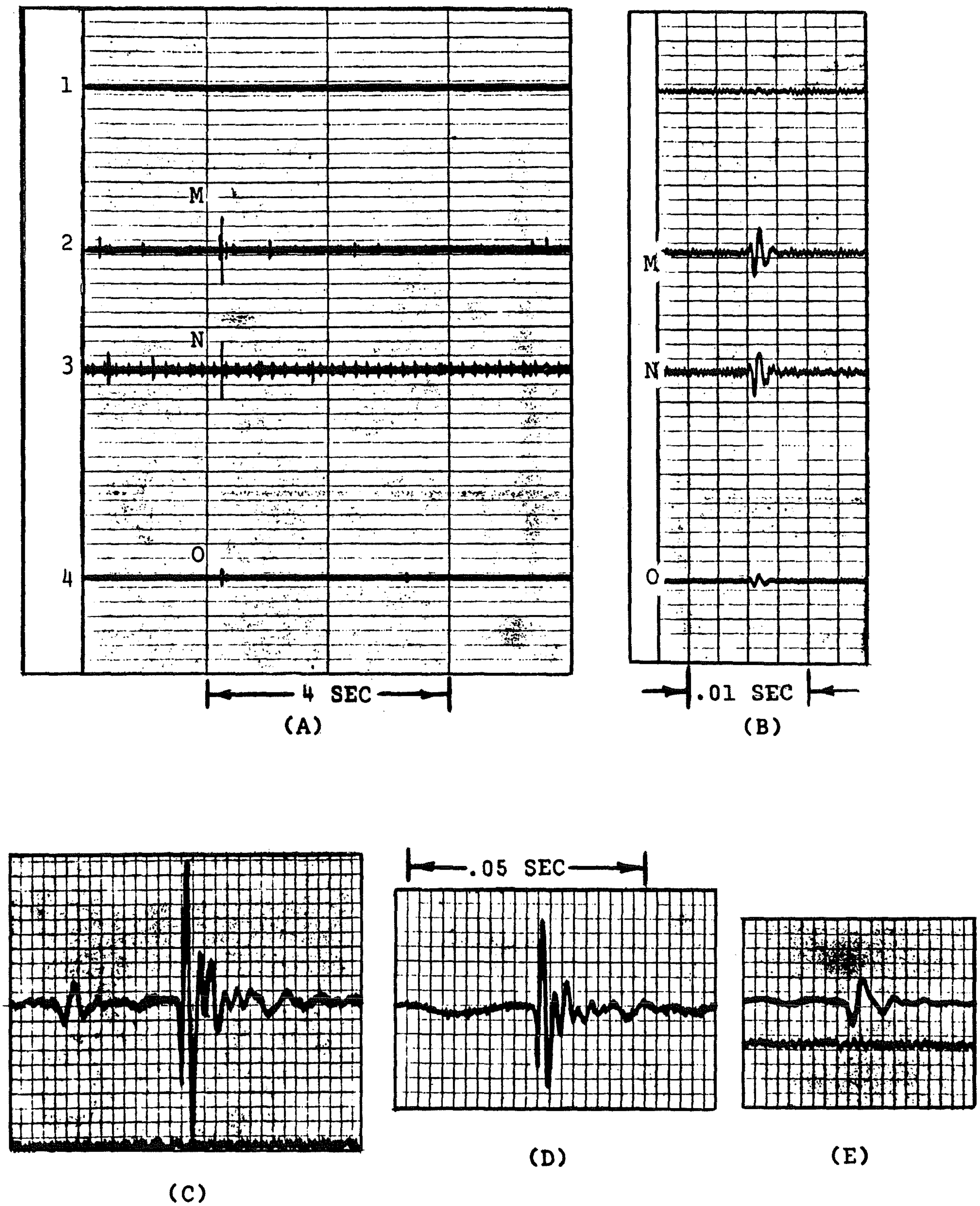

Figure 57 - Typical Microseismic Signals Observed at the A-2 Longwall Site, February 14, 1973 [Record/Playback Filters 0-2500 Hz]

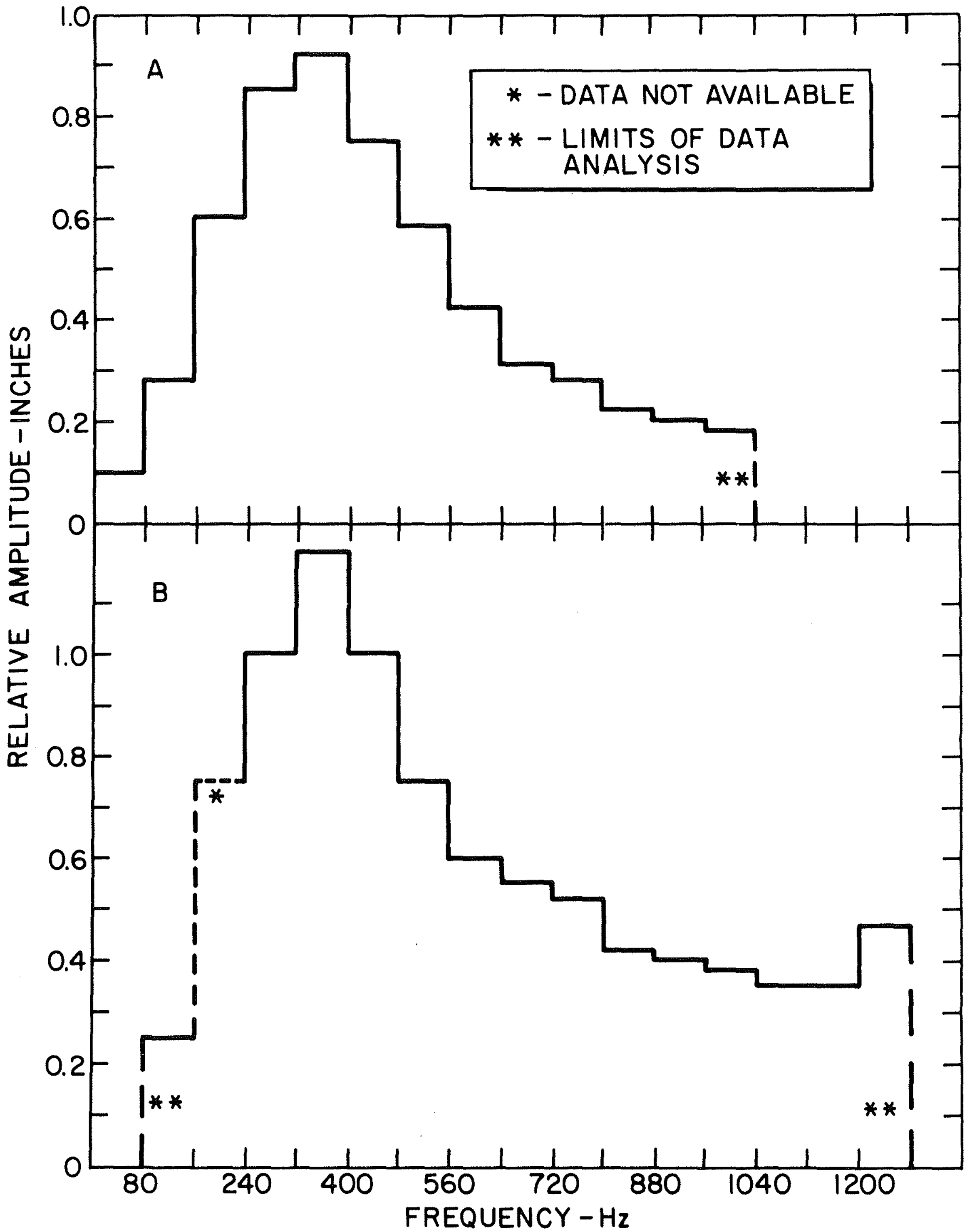

Figure 58 - Frequency Spectra of Two Different Microesismic Signals (A & B) Observed at A-2 Site, February 14, 1973

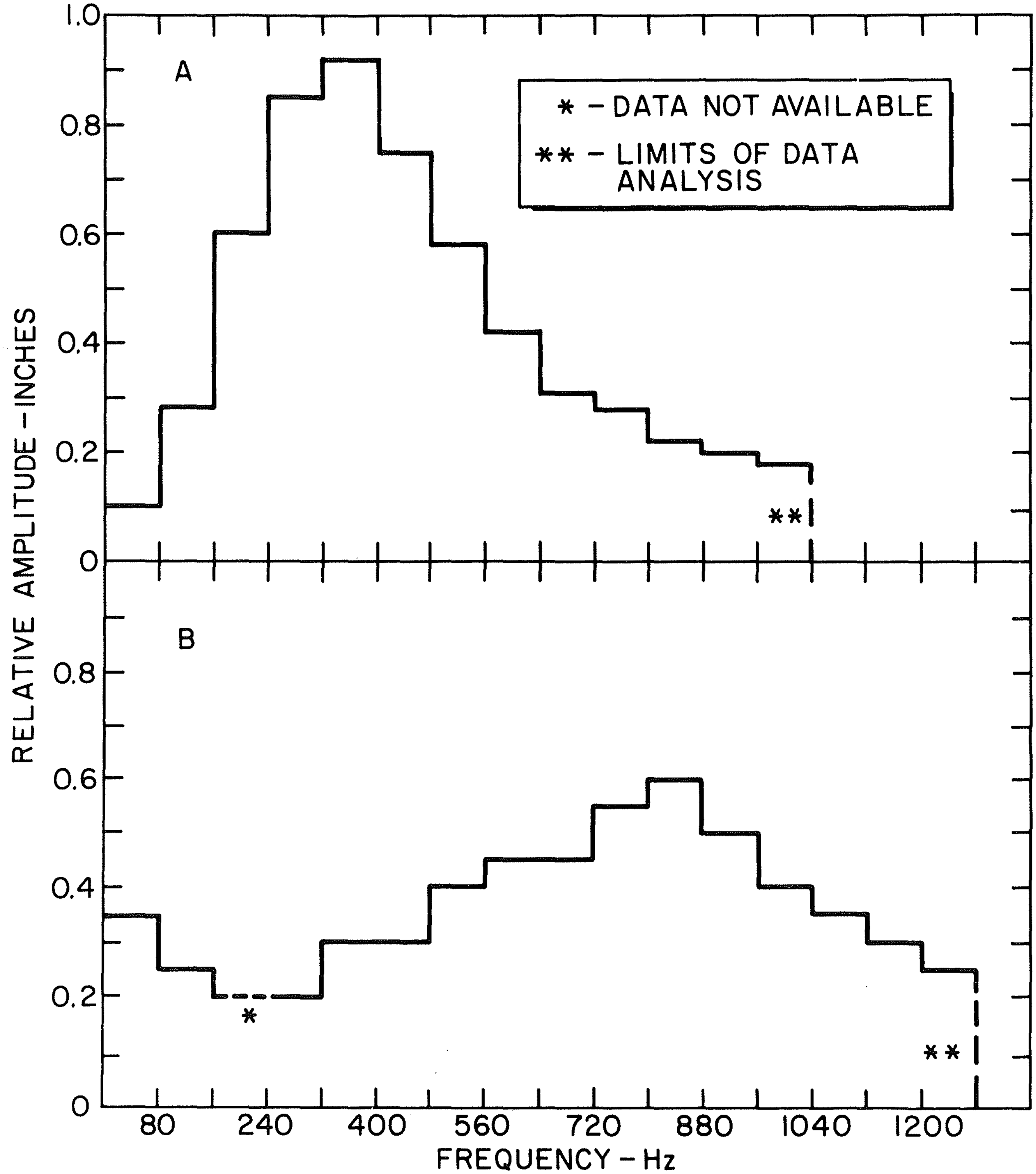

Figure 59 - Comparison of Frequency Spectra of Microseismic Signal (A) and Background (B) Observed at A-2 Site, February 14, 1973

microseismic events have their major energy in the range 160-560 Hz with a pronounced peak around 320 Hz.

Magnetic tapes containing the field data from the study were also processed using sections of the manual analysis system shown earlier (see Figure 38B). In particular, the number of signals on each monitoring channel having amplitudes well above the general background (defined by trigger level set) were counted and recorded on a digital printer. This analysis was carried out for a series of ten minute intervals over the total test period. The results are shown graphically in Figure 60. The fact that the major acoustic emission activity occurs at locations 2, 3 & 4, immediately over the active workings, is further evidence that it is directly associated with mining. There is no positive explanation for the pronounced peaks which occur at approximately 50 minutes. They are probably associated with mining operations, however no underground observations were made during this brief study.

Due to a number of factors, in particular the difficulty of access to the area over the A-2 longwall, further studies were not carried out at this site. However the brief series of measurements made here provided positive proof that strata instabilities occurring during longwall mining could be detected using an array of surface mounted transducers. The results of this site therefore provided the encouragement to proceed with a more detailed study over the adjacent B-4 longwall panel.

3.3 West B-4 Longwall Sites

The encouraging results obtained over the A-2 panel prompted a more detailed study over longwall panel B-4. This panel is located in area F of Figure 41 and the approximate locations of the West B-4 longwall sites are shown in Figure 42. Figure 61 shows a section of the mine map including the west section of the B-4 longwall. Initial studies began at these sites on

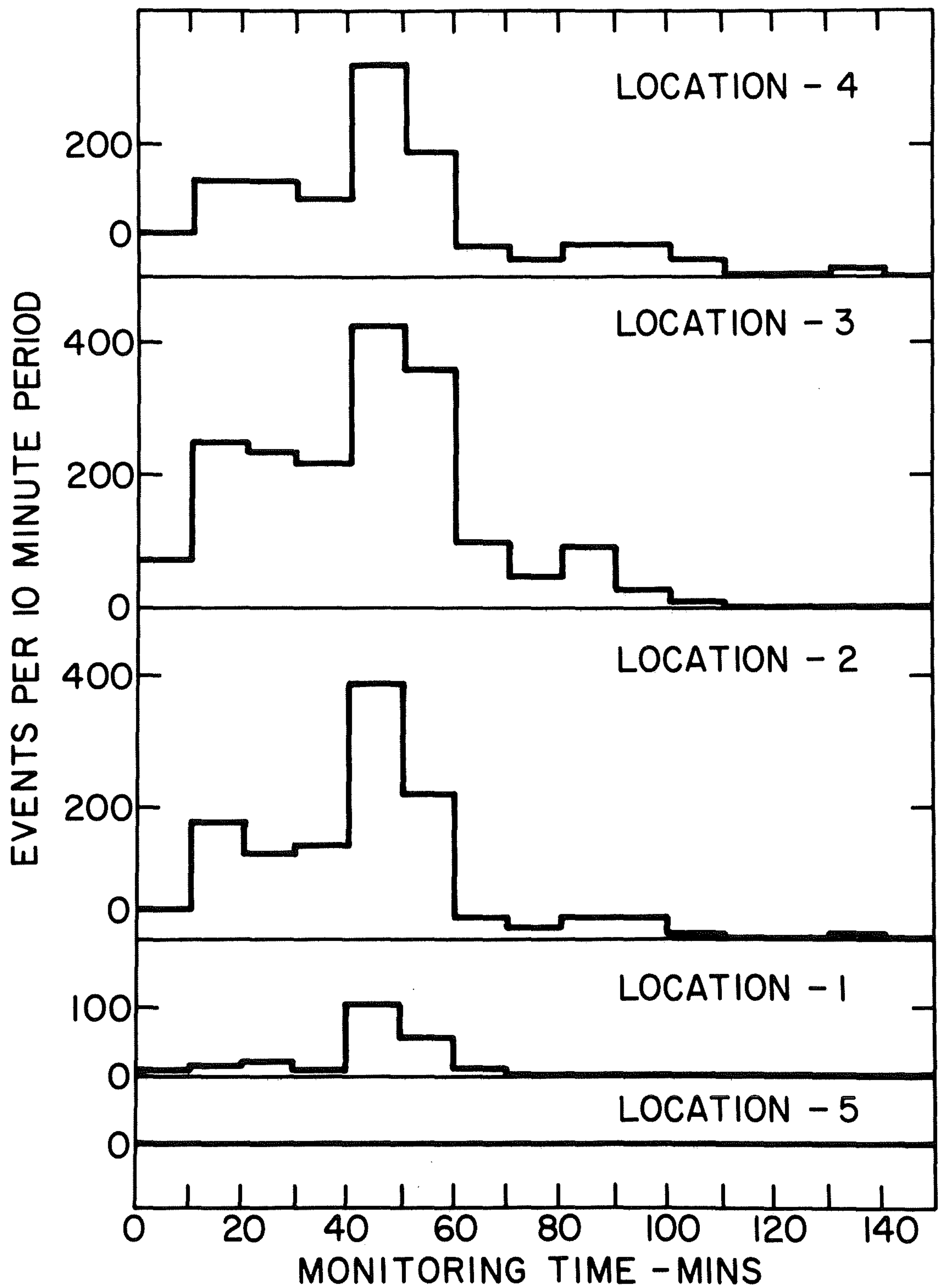

Figure 60 - Variation of Microseismic Activity Rate Observed as a Function of Time for Five Locations at A-2 Site, February 14, 1973

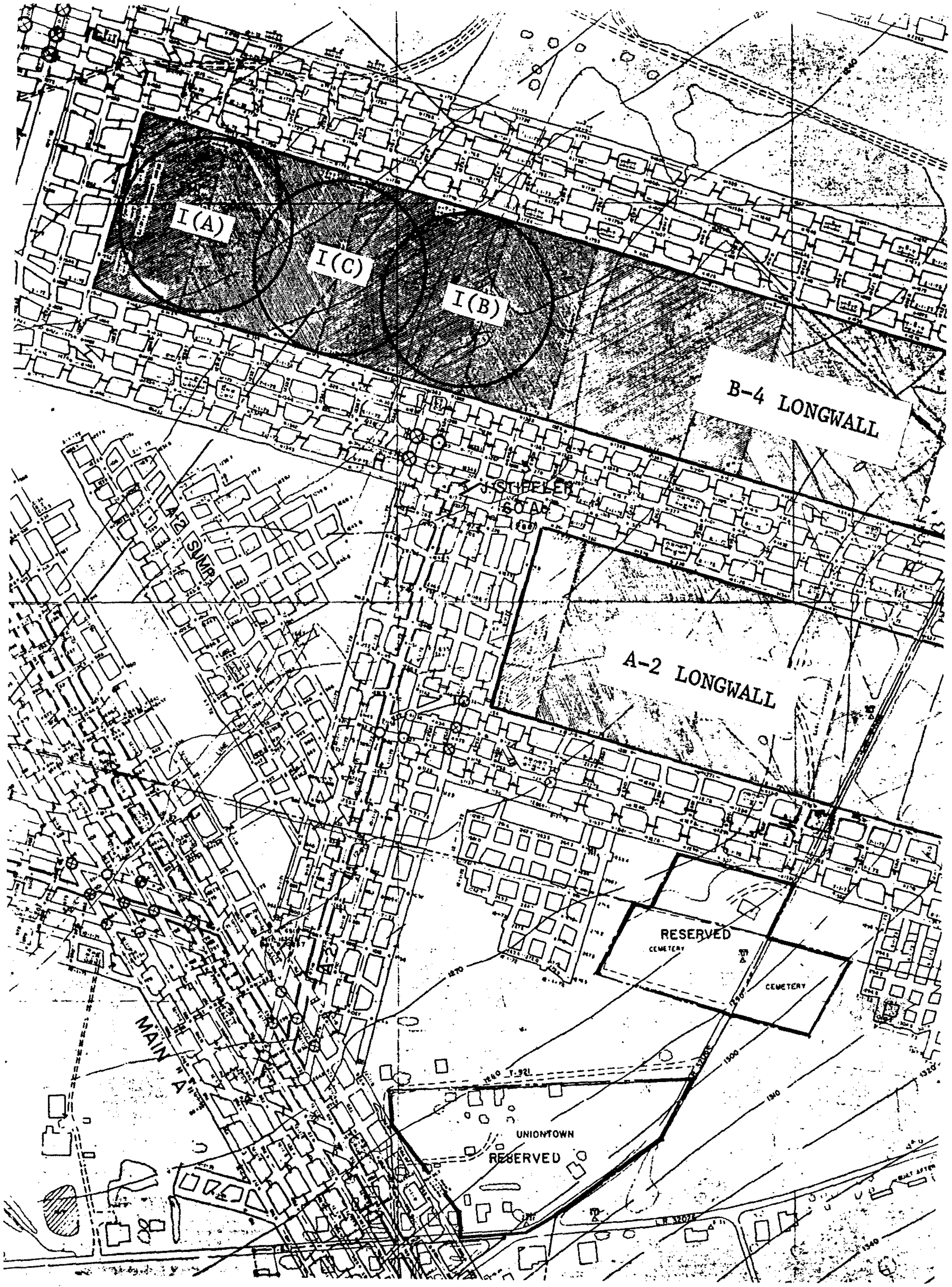

Figure 61 - Map of Section of North Greenwich Mine, Barnesboro, Pa., Showing West B-4 Longwall Sites [I(A), I(B), I(C)]

April 9, 1973 and continued through August 3, 1973. A detailed discussion of the results of these studies will not be included in this report* (since data analysis has been delayed while suitable techniques were developed) however an outline of the overall field program will be included here along with a discussion of typical results.

The field program carried out at this site was as follows:

(1) April 9 - Installation of 7-geophone array over site I(A) [G-1 to G-7]. Geophone locations are shown on Figure 62. Survey data given in Appendix I.

(2) April 10 - Mining of west B-4 panel started.

(3) April 11 - Monitored 2 hours of microseismic data.

(4) April 13 - Longwall had advanced 53 feet. Monitored 2 hours of microseismic data using original array. Enlarged geophone array into site I(C), added six more geophones (G-8 to G-13), see Figure 62. Survey data given in Appendix I.

(5) April 16 - Monitored 1-1/2 hours microseismic data.

(6) April 18 - Longwall had advanced 100 feet. Problems with floor heaving. Monitored 1-1/2 hours microseismic data.

(7) April 26 - Monitored 3-1/2 hours microseismic data.

(8) May 2 - Longwall had advanced 250 feet. Poor caving and floor heaving causing freezing of support chocks. Monitored 3-1/2 hours microseismic data. Three small blasts occurred during monitoring period.

(9) May 7 - Mining stopped 2nd shift.

(10) May 9 - Longwall had advanced 302 feet. Monitored 2-1/2 hours microseismic data.

(11) June 1 - Longwall had advanced 600 feet. Less problems with caving, better floor conditions. Two additional shallow burial geophones installed denoted as 3' and 11', located close to geophones 3 and 11. Monitored 3 hours microseismic data. Project personnel (Gopwani) underground at longwall.

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* Detailed results of the field studies at the west B-4 longwall sites will be included in the final report for Project G0144013 which is presently in progress.

(12) June 20 - Longwall had advanced 950 feet. (This was beyond eastern limits of transducer array.) Problems with roof control, increased chock pressures appeared to improve situation. Monitored 2-1/2 hours microseismic data. Signals appear similar to those observed over A-2 longwall.

(13) July 16-18 - Drilled one deep burial geophone hole at site I(B) using Winkie drill.

(14) July 19/20/23 - Drilled three additional deep burial geophone holes at site I(B) using Winkie drill.

(15) August 1 - Installed deep geophones at I(B) site. Monitored 2 hours microseismic data at I(A) and I(C) sites.

(16) August 3 - Installed three shallow burial geophones at I(B) site near deep geophone locations. Monitored 2 hours microseismic data from shallow and deep burial geophones at I(B) site.

Detailed microseismic studies were completed at the west B-4 longwall sites on Auguust 3, 1973. Since that date however a large number of velocity measurements have been made at these sites.

Figure 62 shows an underground map of the west B-4 longwall area with the approximate location of the shallow burial geophones (G-1 to G-13), located at the I(A) and I(C) sites, indicated. The position of the longwall face on May 2 is also shown along with the approximate location of an underground blast which occurred on that date.

Figures 63 and 64 show a section of microseismic data recorded after the longwall had advanced approximately 175 feet. In this area poor roof caving and heavy floor heaving were being experienced. In both figures data is presented for all seven geophones in the original array. Overall amplifier gain was 60 db. It is interesting to note that geophones 1, 4 and 5 show strong activity but the others show relatively little. The major microseismic energy here appears to be in the range of 200-300 Hz. Figure 63 also shows a signal typical of the hoist noise noted earlier at the air return site.

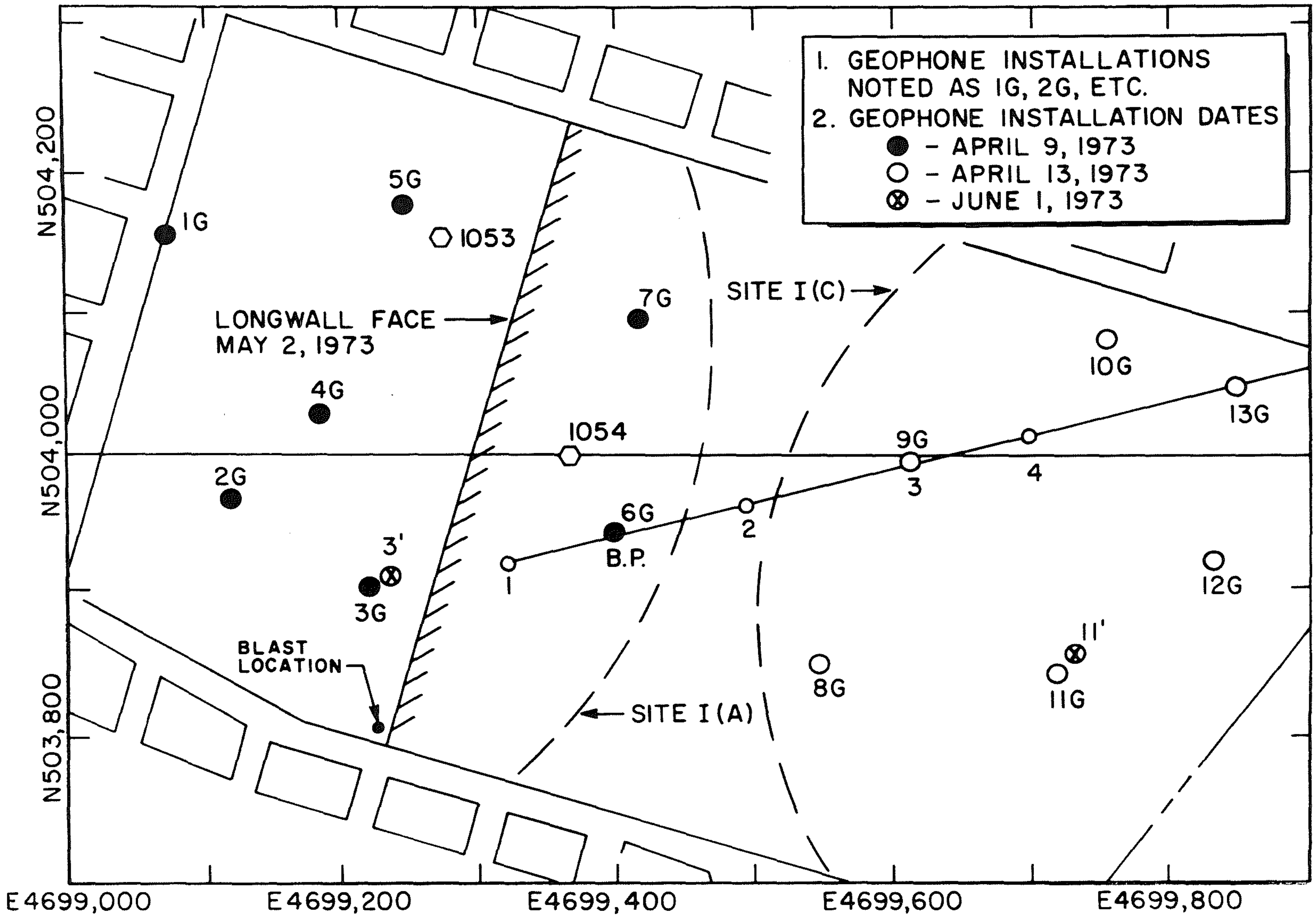

Figure 62 - Approximate Location of Shallow Burial Geophones at Sites I(A) & I(C) West B-4 Longwall

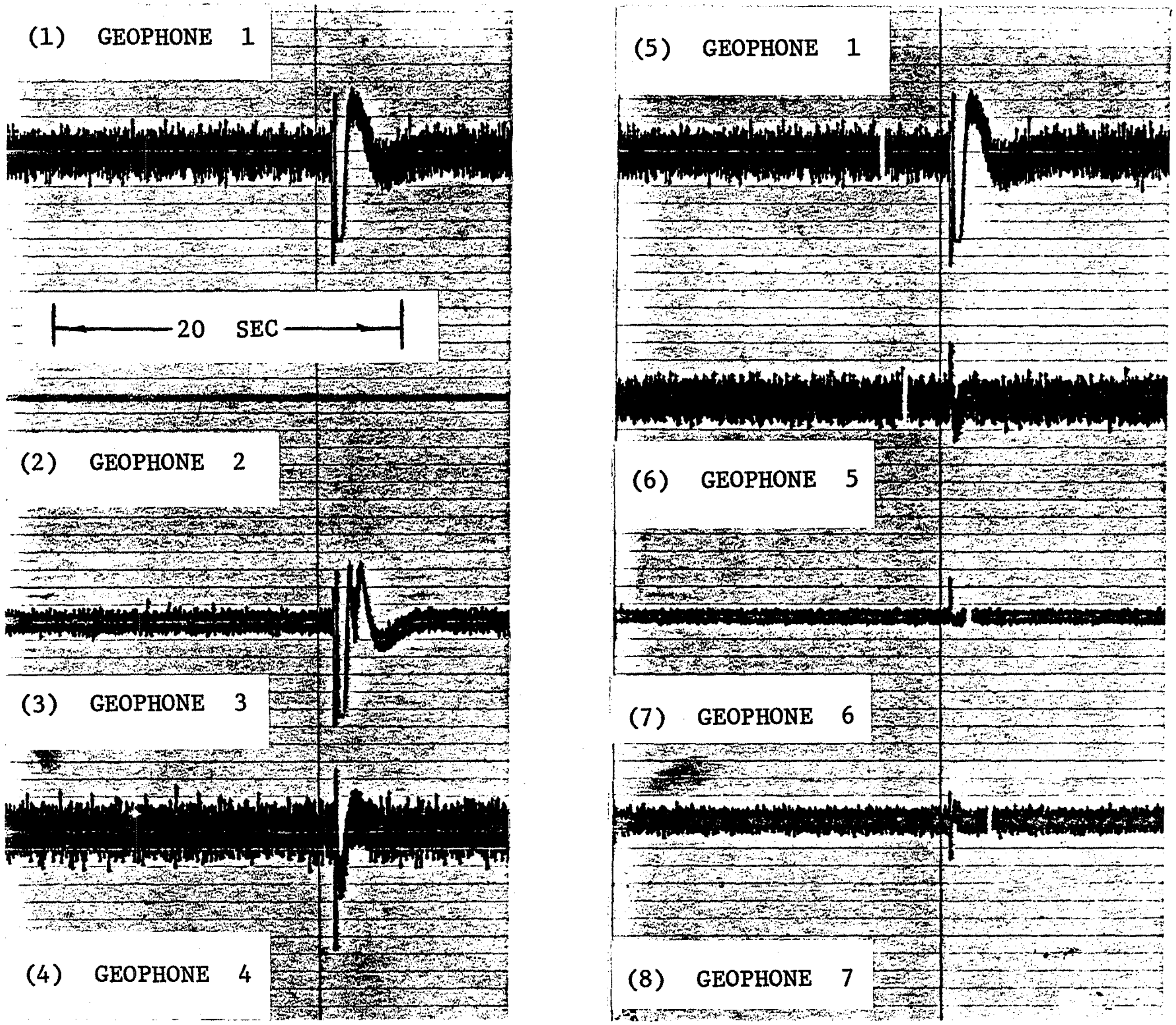

Figure 63 - Typical Microseismic Background Recorded at West B-4 Longwall Site, April 26, 1973 - Slow Speed Playback (Note typical hoist noise similar to that observed at the air return site) [Filters: Record 0-2500 Hz, Playback 0-2500 Hz; Tape Location 17-5770]

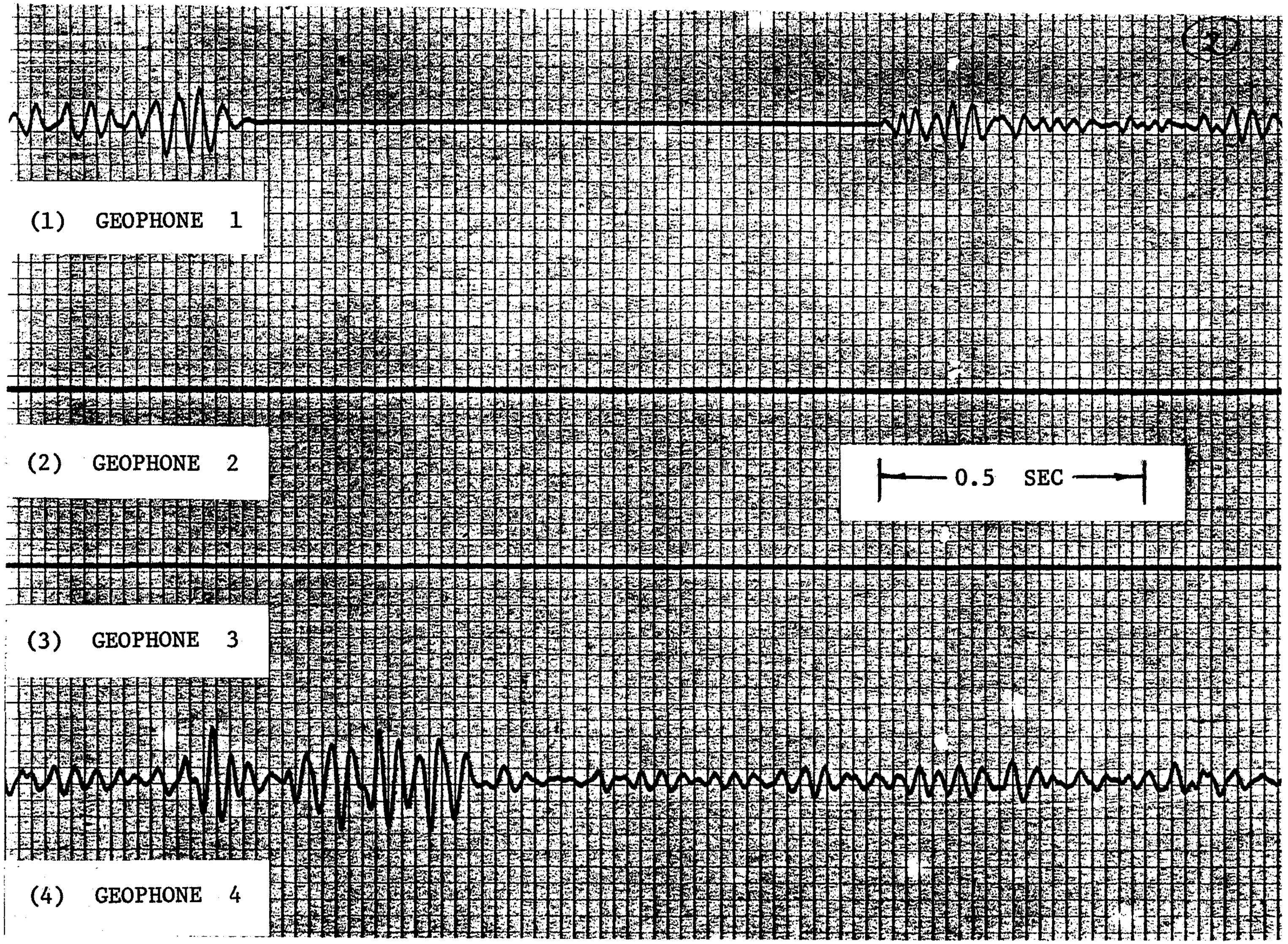

Figure 64 - Typical Microseismic Signals Recorded at West B-4 Longwall Site, April 26, 1973 - Fast Speed Playback [Filters: Record 0-2500 Hz, Playback 200-400 Hz; Tape Location 17-5782]

Figures 65 and 66 show microseismic data recorded after the longwall had advanced 250 feet. Again data from all seven geophones in the original array are shown. Overall amplifier gain was 60 db. Note that in Figure 65 rather extensive playback filtering, 400-600 Hz, has been used whereas in Figure 66 the playback filters were set at 0-100 Hz. The large signal noted on geophones 6 and 7 (located over solid coal) in Figure 66 may well be one of the small underground blasts which occurred on May 2 during attempts to free frozen support chocks. It is interesting to note that geophones 1, 2, 3, 4 and 5, which were at this time over a gob area, did not appear to be influenced by the blast. During these measurements the general background signal frequency appeared to be mainly of the order of 75-100 Hz, whereas frequencies due to the blast itself were of the order of 30-40 Hz.

Microseismic signals observed on June 1, 1973, when the longwall head advanced some 600 feet, are shown in Figures 67 and 68. At this stage the roof behind the longwall was found to be caving much better and floor conditions had improved. Fairly distinct microseismic signals were observed on most geophones, although the signals on geophones 3, 6 and 10 appear weaker than the others. Overall amplification on all geophones was 80 db during these measurements. The frequency of the major microseismic energy appeared to be of the order of 180 Hz.

In general it appears that when poor caving was experienced behind the longwall, along with associated support chocks freezing, relatively poor microseismic signals were detected. In particular microseismic signals were not usually received at all geophones under these conditions. In contrast on June 1 when good caving was occurring specific microseismic events were detected at all geophones.

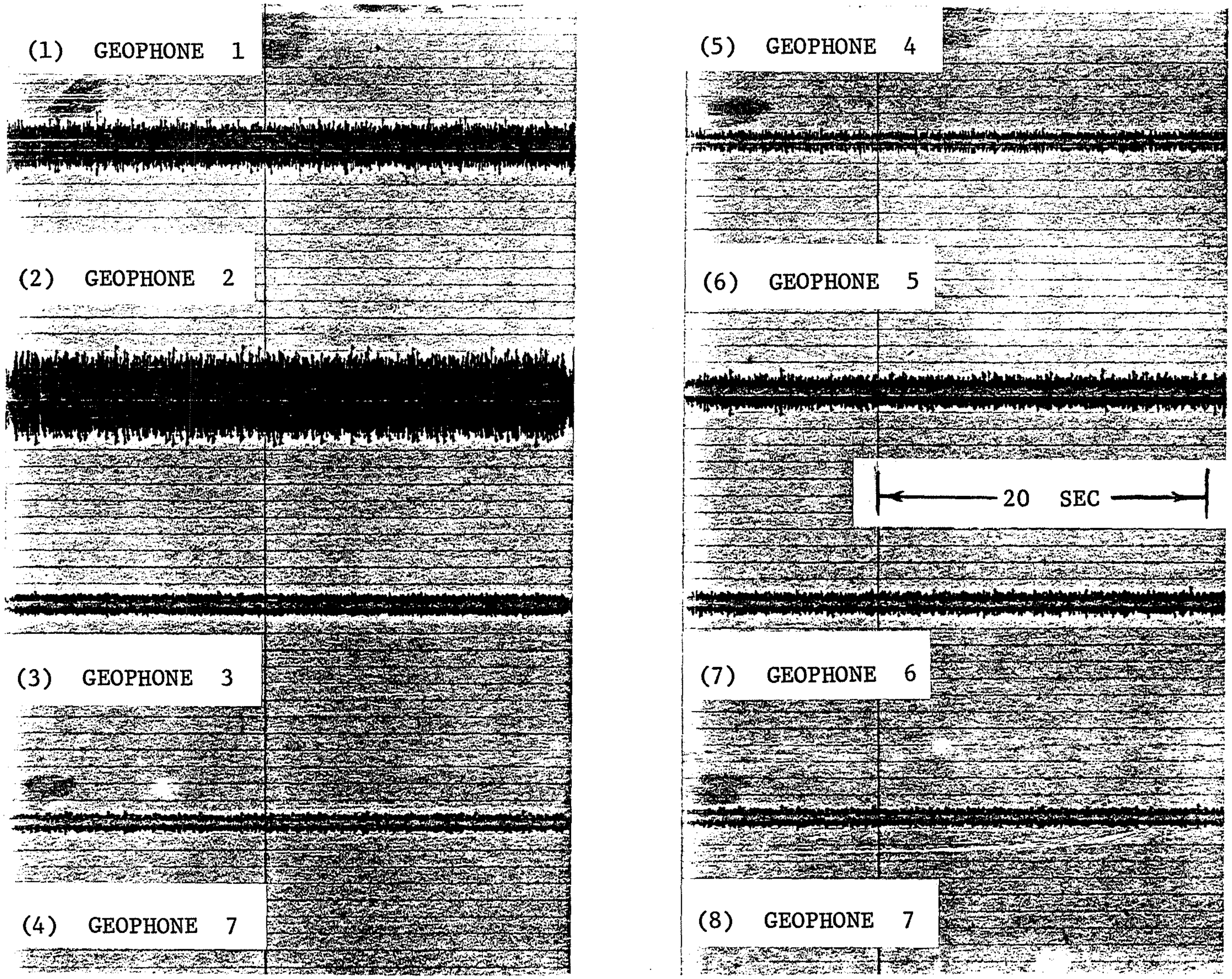

Figure 65 - Typical Microseismic Background Recorded at West B-4 Longwall Site, May 2, 1973 - Slow Speed Playback [Filters: Record 0-2500 Hz, Playback 400-600 Hz; Tape Location 18-3380]

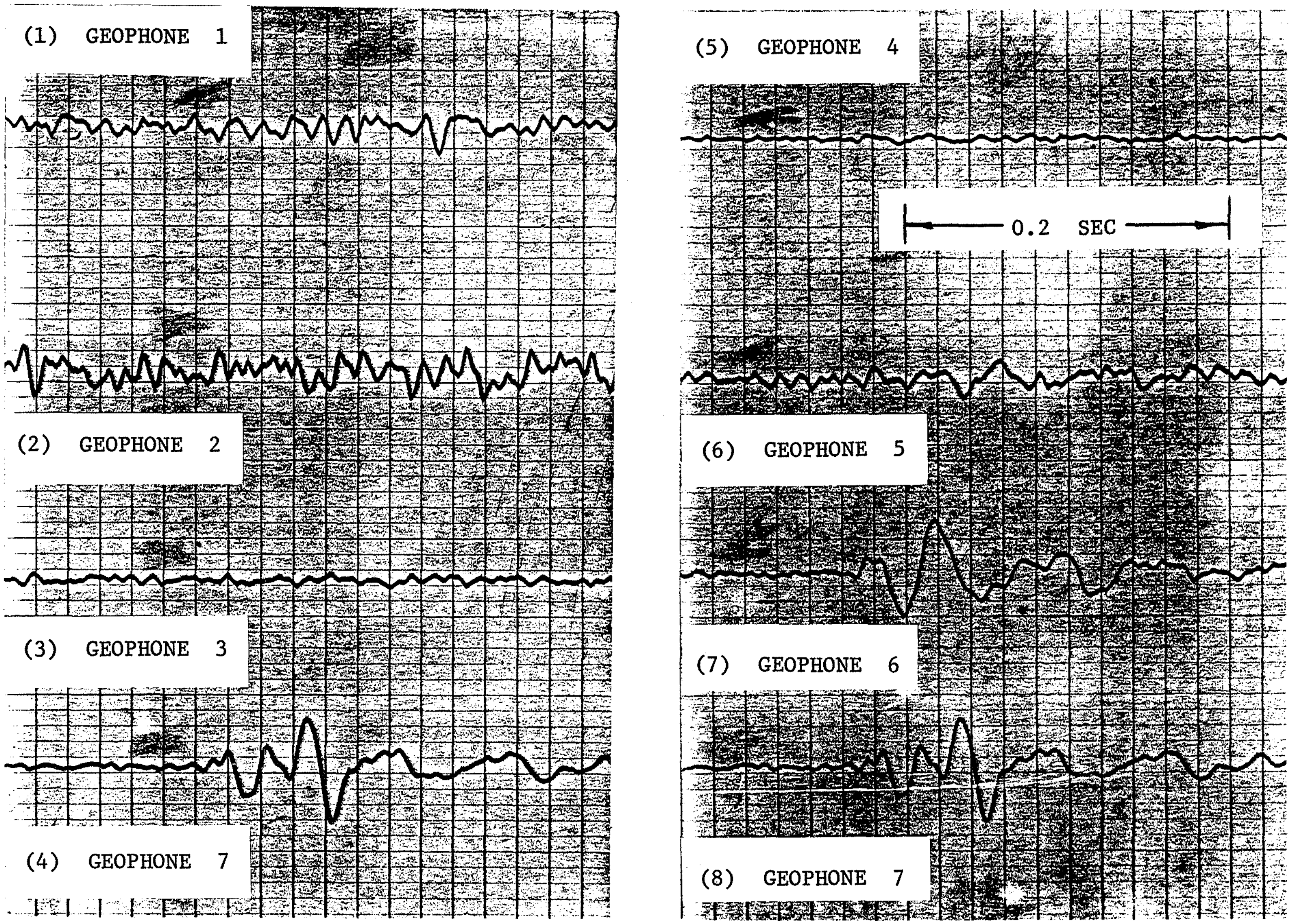

Figure 66 - Typical Microseismic Signals Recorded at West B-4 Longwall Site, May 2, 1973 - Slow Speed Playback [Filters: Record 0-2500 Hz, Playback 0-100 Hz; Tape Location 18-3392]

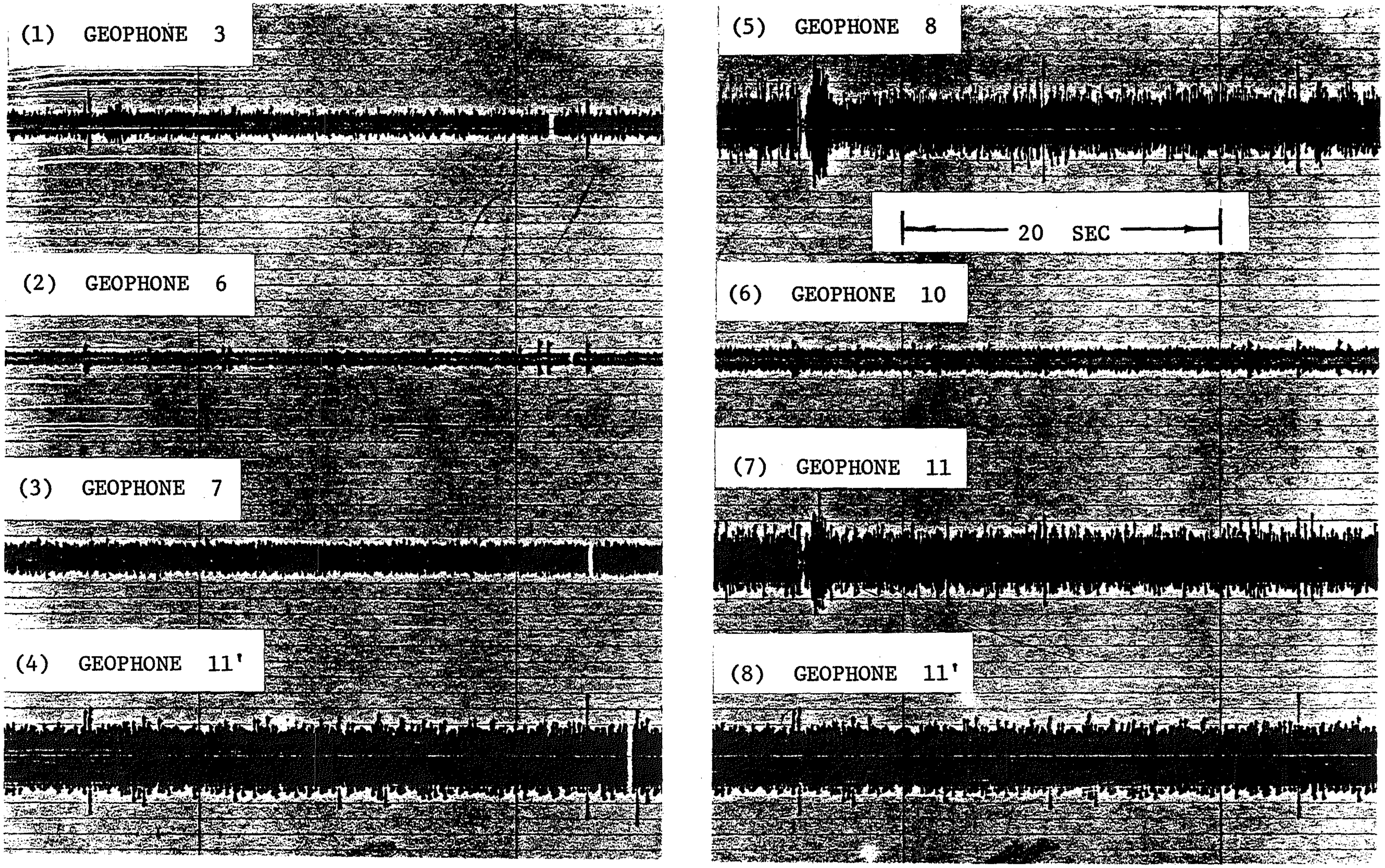

Figure 67 - Typical Microseismic Signals Recorded at West B-4 Longwall Site, June 1, 1973 - Fast Speed Playback [Filters: Record 0-2500 Hz, Playback 200-400 Hz; Tape Location 20-1175]

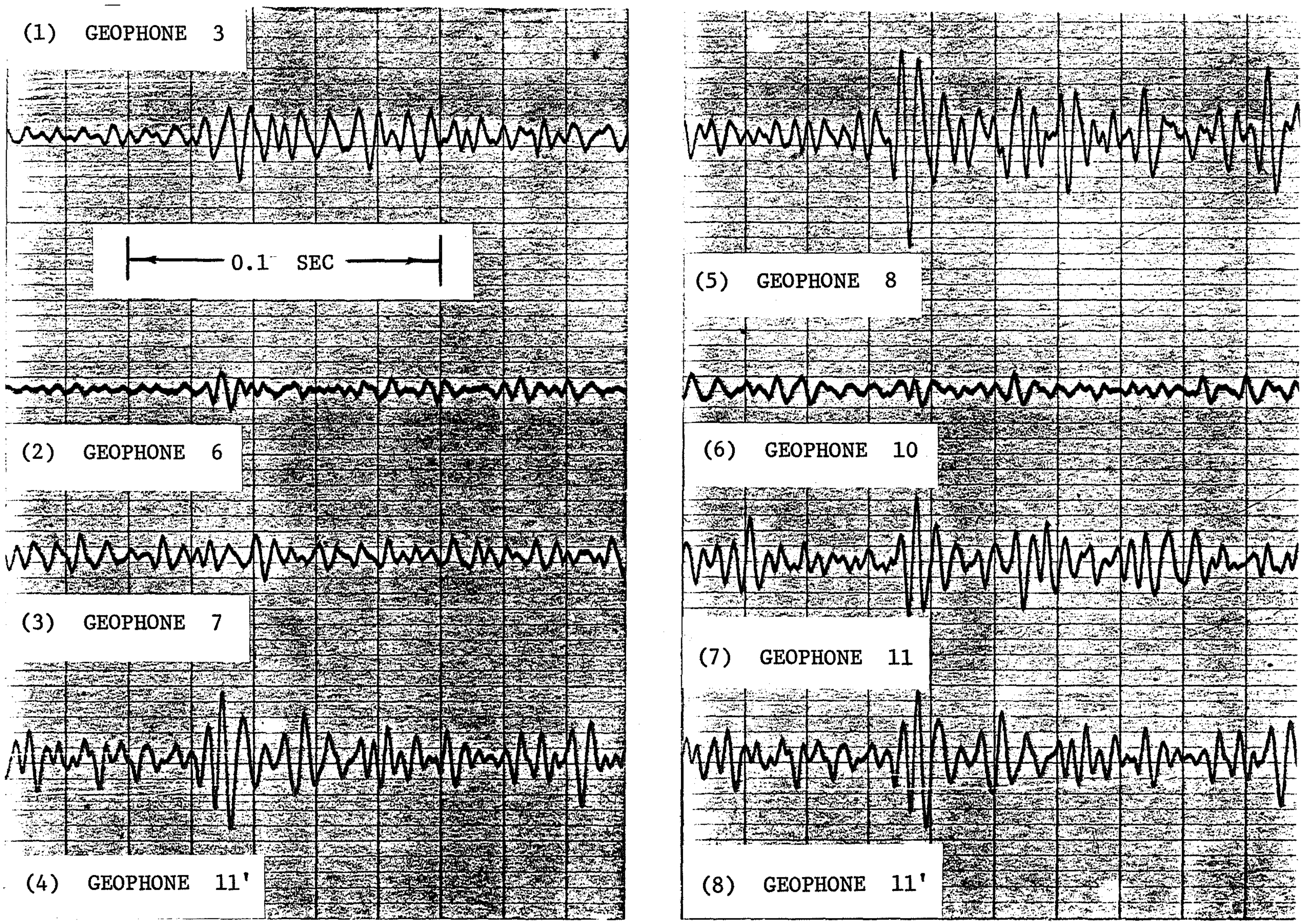

Figure 68 - Typical Microseismic Signals Recorded at West B-4 Longwall Site, June 1, 1973 - Slow Speed Playback [Filters: Record 0-2500 Hz, Playback 100-200 Hz; Tape Location 20-1203]

During the west B-4 longwall studies, a special effort was taken to correlate underground activity with recorded microseismic data. When possible, one of the project team was located underground at the longwall making a continuous record of all operations (machines in use, prop positions, roof control problems, etc.) for later time correlation with surface microseismic measurements.

The limited field data on the west B-4 longwall site presented in this section has been included only as an example of typical microseismic data observed during this longwall operation. Detailed analysis of the large volume of data actually recorded at this site is presently underway and results will be presented in a later report.

4. Discussion

The various field studies described in this chapter have indicated that detection of underground instabilities (e.g. roof fracturing due to longwall operations, floor blasting, ect.) using a surface microseismic array is feasible although difficult with the techinques used todate. In many cases obvious relatively large underground explosions were not even detected by all geophones in the array. Furthermore in many cases signals were all but buried in noise. Much of the problem was considered to be associated with the geophone installation itself, in particular the quality of the coupling between the geophone and the strata. There appeared to be little doubt that to obtain satisfactory coupling geophones would have to be installed deeper, hopefully in solid rock, and probably cemented in place. Preliminary studies using this type of installation were attempted at the west B-4 site during July 1973 and results appeared encouraging.

In the Fall of 1973 this concept was tested in detail by installing a geophone array over the east end of the B-4 longwall at the I(D) site shown earlier in Figure 42. This array was associated with a longwall study undertaken as part of a new U.S.B.M. microseismic project initiated October 1, 1973.

On October 16, 1973, fifteen geophone locations were established in the primary test area (see site I(D), Figure 42) and arrangements were made for commercial augering of transducer installation holes at each location. These holes were drilled on October 22 and 23 by the Tinney Drilling Company, and geophones were cemented in position immediately following drilling. On October 26, after the cement had fully set, the remainder of the open section of each borehole was filled with sand in order to prevent the accumulation of ground water. During the period November 1973 to February 1974 a series of measurements were made to ascertain the microseismic background activity at this test site as the longwall approached the area. On February 18 the first positive multi-channel microseismic events at the Greenwich mine were recorded over the B-4 longwall panel at the new test site. Figures 69 and 70 show records of a number of typical multi-channel events. Such data has continued to be obtained on subsequent field trips.

There is little doubt that the new type of transducer installation has completely resolved earlier monitoring problems. Excellent signal-to-noise figures have been obtained ranging up to 10-15, and most underground events are now detected by all geophones in the array. A detailed presentation of data from the east B-4 longwall site will be presented in a later report.

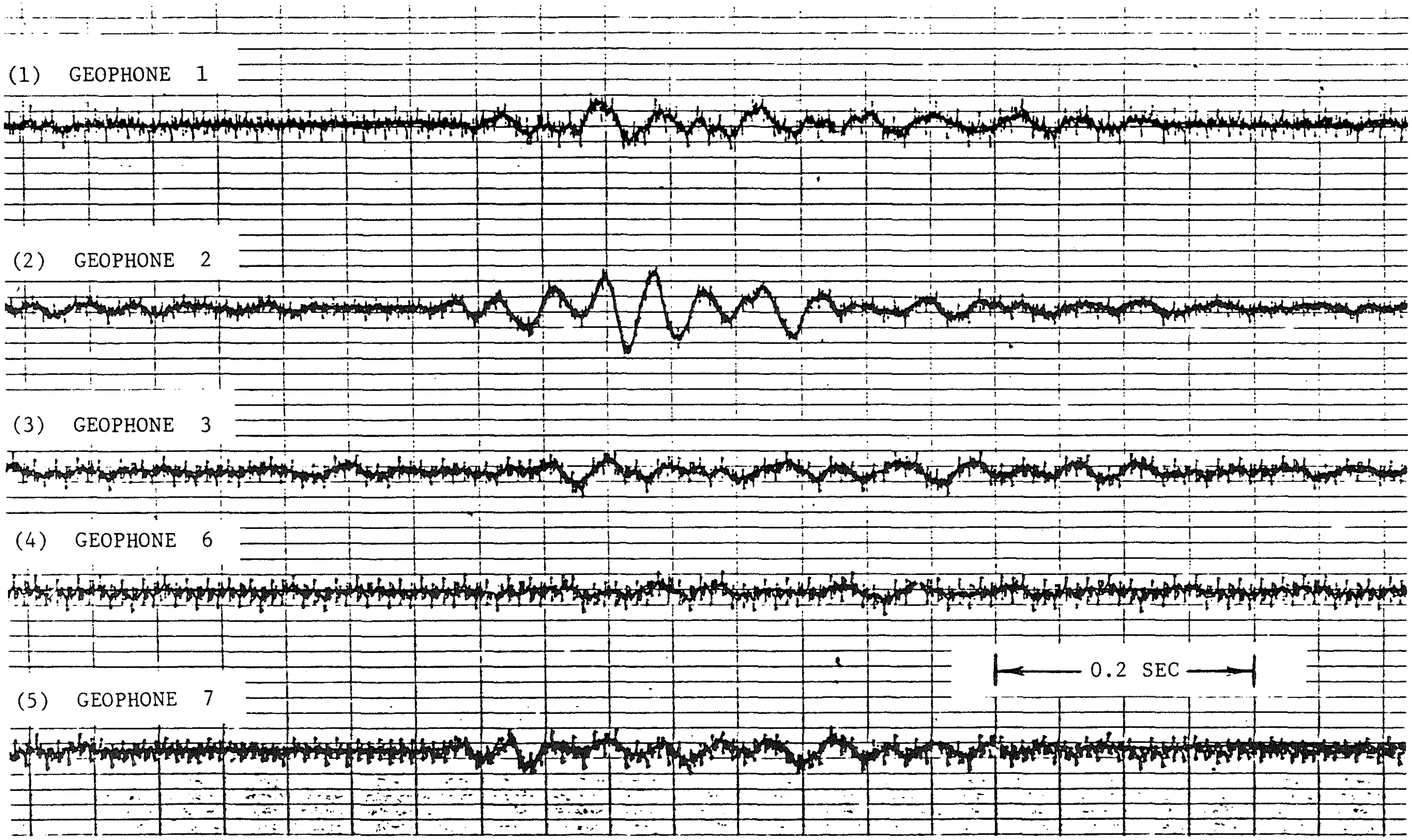

Figure 69 - Typical Multi-Channel Microseismic Events Monitored at Greenwich East B-4 Longwall Site [I(D)] on February 18, 1974 [Filter record/playback 1000 Hz, Tape location 36-759A]

Figure 70 - Typical Multi-Channel Microseismic Events Monitored at Greenwich East B-4 Longwall Site [I(D)] on February 18, 1974 [Filter record/playback 0-1000 Hz, Tape location 36-261]

GENERAL DISCUSSION

Although detailed analysis of data obtained during the recent microseismic studies at the Greenwich Colliery in central Pennsylvania have not as yet been completed, the following conclusions are evident:

(1) The feasibility of monitoring underground strata instability using microseismic transducers installed in surface locations has been positively verified.

(2) The mobile microseismic monitoring facility designed specifically for these studies has proven to be most successful. Field measurements using this facility have developed into a relatively simple, routine operation.

(3) Field techniques and in particular transducer installation have undergone a considerable metamorphism during the recent project. Final transducer installation techniques appear to be optimum.

(4) Microseismic measurements have been made at an active coal mine site for a period of over one year. During this time studies were conducted over a previously mined development area, and two active longwall wall sections. Positive microseismic signals were obtained for both longwall sites, however few signals of positive microseismic origin were detected over the development area.

(5) In the case of the more recent of the two longwall studies (west B-4 site), it was observed that the character of the microseismic data observed on surface depended on the operating conditions of the associated longwall. For example under poor conditions (unsatisfactory roof failure behind the support system and resulting bad floor conditions) microseismic signals were not received at all locations in the transducer array, and the frequency content of the signals were relatively high. In contrast under good longwall conditions microseismic signals were of lower frequency content, and were generally received on all transducers in the array. It is apparent therefore that in the future certain microseismic parameters may become extremely useful for characterizing the efficiency and safety of longwall operations.

(6) Current studies in progress at a third Greenwich longwall site have been a complete success. In these studies it appears that microseismic activity has also been observed which was associated with surface subsidence. The character of the observed signals due to underground and surface instabilities have been found to be quite different.

(7) More sophisticated computer techniques for signal recognition and analysis are required to make efficient use of observed microseismic data. This is due in part to the fact that the mechanical instabilities associated with normal mining operations (e.g. longwall) are considerably smaller than those associated with major instabilities, such as rock or coal bursts, for which major analysis efforts have been concentrated in recent years. Studies associated with this problem are presently under way utilizing the Penn State hybrid computer.

At present a number of factors still limit the usefulness of microseismic techniques in efficiently evaluating the stability of geologic structures such as underground coal mines, namely:

(1) Difficulty in separating microseismic signals from ambient background noise.

(2) Inability in most geologic structures to obtain an equivalent unloaded condition in order to evaluate local background noise.

(3) Large dimensions of most geologic structures and resulting attenuation (usually highly frequency dependent) of microseismic signals with distance from their source.

(4) Electrical and mechanical difficulties in instrumenting such structures.

(5) Difficulty in source location due to lack of information on propagation velocities, and the normally anisotropic velocity characteristics of geologic materials.

In spite of these limitations microseismic techniques have proven increasingly useful in such applications in recent years. Results of the study contained in this report provide further evidence of the usefulness of microseismic techniques in strata control and associated mine safety monitoring. With the development of better monitoring facilities, improved transducers and field installation techniques, and development of computer based analysis methods, the successful application of microseismic techniques to stability evaluation of geologic structures should increase manyfold.

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The majority of the field studies themselves were carried out by Dr. A. W. Khair, Dr. R. Y. Kim and E. J. Kimble, Mining Section staff attached directly to the project. A number of departmental graduate assistants contributed a great deal to the study and in particular the assistance of L. A. Beck, J. W. Comeau, M. Gopwani, S. T. Harding and G. L. Mowrey is gratefully acknowledged. The field studies associated with this project involved long hours often under extremely difficult working conditions. The author was fortunate to have the assistance of such a hard working and unselfish field research group.

REFERENCES

[1] Scott, J. J., "Key Note Address," Proceedings of Conference on Underground Mining Environment, University of Missouri-Rolla, Rolla, October 27-29, 1971, pp. 1-15.

[2] Hardy, H. R., Jr., "Application of Acoustic Emission Techniques to Rock Mechanics Research," ASTM, STP 505, pp. 41-83.

[3] Hardy, H. R., Jr., "Evaluating the Stability of Geologic Structures Using Acoustic Emission," ASTM Symposium on Monitoring Structural Integrity by Acoustic Emission, (Ft. Lauderdale, 1974). Symposium Proceedings in Press.

[4] Obert, L., "Measurement of Pressures on Rock Pillars in Underground Mines. Part I.," U. S. Bureau of Mines RI 3444, 1939.

[5] Obert, L., "Measurement of Pressures on Rock Pillars in Underground Mines. Part II.," U. S. Bureau of Mines RI 3521, 1940.

[6] Obert, L., "Use of Subaudible Noise for Prediction of Rock Bursts," U. S. Bureau of Mines RI 3555, 1941.

[7] Obert, L. and W. I. Duvall, "Use of Subaudible Noise for Prediction of Rock Bursts. Part II.," U. S. Bureau of Mines RI 3654, 1942.

[8] Obert, L. and W. I. Duvall, "Microseismic Method of Predicting Rock Failure in Underground Mining. Part I. General Method," U. S. Bureau of Mines RI 3797, 1945.

[9] Obert, L. and W. I. Duvall, <u>Rock Mechanics and the Design of Structures in Rock</u>, John Wiley & Sons, Inc., New York, 1967.

[10] Cook, N. G. W., "The Seismic Location of Rockbursts," <u>Proceedings Fifth Symposium on Rock Mechanics</u> (Minneapolis 1962), pp. 493-516, Pergamon Press, New York, 1963.

[11] Blake, W., "Rock Burst Mechanics," Quarterly of Colorado School of Mines, Vol. 67, No. 1, 64 pp., 1972.

[12] Blake, W., "Rock Burst Research at the Galena Mine, Wallace, Idaho," U. S. Bureau of Mines, TPR 39, 22 pp., 1971.

[13] Blake, W. and W. I. Duvall, "Some Fundamental Properties of Rock Noises," Trans. SME, Vol. 244, pp. 288-290, 1969.

[14] Blake, W. and F. Leighton, "Recent Developments and Applications of the Microseismic Method in Deep Mines," <u>Proceedings Eleventh Symposium on Rock Mechanics</u> (Berkeley 1969), AIME, New York, 1970, pp. 429-443.

[15] Leighton, F. and W. Blake, "Rock Noise Source Location Techniques," U. S. Bureau of Mines, RI 7432, 1970.

[16] Oudenhoven, M. S. and R. E. Tipton, "Microseismic Source Locations Around Block Caving at the Climax Molybdenum Mine," U. S. Bureau of Mines, RI 7798, 1973.

[17] Buchheim, W., "Geophysical Methods for the Study of Rock Pressure in Coal and Potash - Salt Mining," International Strata Control Congress, Leipzig, 1958, pp. 222-233.

[18] Neyman, B. and W. Zuberek, "Seismoakustische Forschungen zum Gebirgschlagproblem," Freiberger Forschungshefte C 225, Geophysik, 1967, pp. 44-61.

[19] Neyman, B., Z. Grabis, M. Trombik, and W. Zuberek, "Results of Investigations in the Bobrek Mine on Pressure and Rock Bursts Using Seismoacoustic Methods," Prace GIG Komunikat nr 464, Katowice, 1969, Ślask.

[20] Wierzchowska, Z., "Fundamentals and Method System for Conducting Microseismological Observations in Mines for Assessing Degree of Rocks Burst Hazard," Przeglad Górniczy, Vol. XXVII, No. 11, 1971, pp. 503-511.

[21] Zuberek, W., "Analysis of the Course of Seismoacoustic Activity in the Case of Rock Burst Provoked by Shotfiring," Prace GIG Komunikat nr 533, Katowice, 1971.

[22] Neyman, B., Z. Szecówka, and W. Zuberek, "Effective Methods for Fighting Rock Bursts in Polish Collieries," Proceedings Fifth International Strata Control Conference (London, 1972).

[23] Neyman, B., H. Sokolowski, M. Trombik, and W. Zuberek, "Stationary and Portable Seismoacoustic Apparatus," Bezpieczeństwo Pracy w Górnictwie, 1972 (in press).

[24] Stas, B., et al., "Development Trends and Application of Geophysical Research in Mines of the Ostrava-Karvina Coal Field," Proceedings Twelfth Symposium on Rock Mechanics (Rolla, 1970), AIME, New York, 1971, pp. 109-119.

[25] Antsyferov, M. S., (Editor), "Seismo-Acoustic Methods in Mining," Consultants Bureau, New York, 1966.

[26] Brauner, G., "BeKampfung der Gebirgsschlaggefahr: Entwicklung von Betriebsverfahren 1963-1971," Gluckauf-Betriefsbucher, Band 16, pp. 66-68, Essen, 1973.

[27] Broadbent, C. D. and C. W. Armstrong, "Design and Application of Microseismic Devices," Proceedings Fifth Canadian Rock Mechanics Symposium (Toronto, 1968), pp. 91-103, Published Department of Energy, Mines and Resources, Ottawa, 1969.

[28] Paulsen, J. C., R. B. Kistler, and L. L. Thomas, "Slope Stability Monitoring at Boron," Mining Congress Journal, Vol. 53, 1967, p. 28.

[29] Wisecarver, David W., R. H. Merrill, and R. M. Stateham, "The Microseismic Technique Applied to Slope Stability," Trans. SME, Vol. 244, December 1969, pp. 378-385.

[30] Hardy, H. R., Jr. and A. W. Khair, "Applications of Acoustic Emission in the Evaluation of Underground Gas Storage Reservoir Stability," Proceedings Ninth Canadian Symposium on Rock Mechanics (Montreal, 1973), (in press).

[31] Crandell, F. J., "Determination of Incipient Roof Failures in Rock Tunnels by Microseismic Detection," Jour. Boston Soc. Civil Engineers, January 1955, pp. 39-59.

[32] Beard, F. D., "Microseismic Forecasting of Excavation Failures," Civil Engineering, Vol. 32, No. 5, 1962, pp. 50-51.

[33] Cadman, J. D., R. E. Goodman, and C. Van Alstine, "Research on Subaudible Noise in Landslides," Geotechnical Engineering Report on Investigation (NSF Grant GK 109), June 27, 1967, Department of Civil Engineering, University of California, Berkeley.

[34] Goodman, R. E. and W. Blake, "Microseismic Detection of Potential Earth Slumps and Rock Slides," Report No. MT-64-6, Inst. of Engineering Research, Univ. of California, Berkeley, 1964.

[35] Goodman, R. E. and W. Blake, "An Investigation of Rock Noise in Landslides and Cut Slopes," Felsmechanik and Ingenieurgeologie, Supplement II, 1965.

[36] Goodman, R. E. and W. Blake, "Rock Noise in Landslides and Slope Failures," Highway Research Board, 44th Annual Meeting N. 119, Washington, D. C., 1966.

[37] Hardy, H. R., Jr. and E. J. Kimble, Jr., "Design and Development of a Mobile Microseismic Monitoring Facility," Internal Report RML-IR/72-20, Department of Mineral Engineering, The Pennsylvania State University, 1972.

[38] Morrison, R., Grounding and Shielding Techniques in Instrumentation, John Wiley & Sons, Inc., New York, 1967.

[39] Hardy, H. R., Jr., R. Y. Kim, and J. W. Comeau, "Development of a Borehole Probe for Detection of Microseismic Activity," Internal Report RML-IR/74-4, Department of Mineral Engineering, The Pennsylvania State University, 1974.

[40] Comeau, J. W., Design and Development of a Microseismic Borehole Probe, M.S. Thesis, Department of Mineral Engineering, The Pennsylvania State University, 1974.

[41] Mowrey, G. L., "Computerized Data Processing Programs for Use with a Multichannel Analog Microseismic Data Acquisition System," Internal Report RML-IR/74-5, Department of Mineral Engineering, The Pennsylvania State University, 1974.

[42] Yonkoske, J. W., "Incompetent Roof Conditions at Greenwich Collieries North Portal," Internal Report RML-IR/72-26, Department of Mineral Engineering, The Pennsylvania State University, 1972.

[43] Fettke, C. R., "Structural Contour Maps of the Plateau Region of North-central and Western Pennsylvania," Topographic and Geologic Survey Bull., G27, p. 25, 1954.

[44] Moore, R. C., Historical Geology, McGraw-Hill, New York, 1933.

[45] Weller, J. M., "Cyclical Sedimentations in the Pennsylvanian and Its Significance," Jour. Geol., Vol. 38, No. 2, pp. 97-135, 1930.

[46] Jones, M. F., III, "Development of Stratigraphic Cross-Sections from Selected Drill Holes at the Greenwich Colliery, Barnesboro, Pennsylvania," Internal Report RML-IR/72-13, Department of Mineral Engineering, 1972.

[47] Kim, R. Y., "Literature Survey on the Propagation Characteristics of Stress Waves in Coal and Coal Measure Rocks, and the Strength and Deformation Properties of Coal," Internal Report RML-IR/70-25, Department of Mining, The Pennsylvania State University, 1970.

[48] Kim, R. Y., "Preliminary Study of Velocity and Absorption of Stress Waves in Coal Measure Rocks Using Ultrasonic Techniques," Internal Report RML-IR/70-26, Department of Mining, The Pennsylvania State University, 1970.

[49] Kim, R. Y., "Study of Velocity and Absorption of Stress Waves in Coal Measure Rocks Using Ultrasonic Techniques - Part I," Internal Report RML-IR/71-18, Department of Mineral Engineering, The Pennsylvania State University, 1971.

[50] Kim, R. Y., "Studies of Velocity and Absorption of Stress Waves in Coal Measure Rocks Using Ultrasonic Techniques - Part II," Internal Report RML-IR/72-7, Department of Mineral Engineering, The Pennsylvania State University, 1972.

[51] Hardy, H. R., Jr., R. Stefanko, and E. Kimble, "An Automated Test Facility for Rock Mechanics Research," Inter. Jour. Rock Mechanics Mining Science, Vol. 8, pp. 17-28, 1971.

APPENDIX A

Specifications of Equipment and Components in Mobile Microseismic Monitoring Facility

For convenience, a brief review of the electrical and mechanical specifications of the various pieces of electronic equipment as well as the van and trailer itself are included in this Appendix.

1. Preamplifier

   1.1 Ithaco Model 144 L

   1.2 Voltage Gain: 40 db ± 0.2 db @ midband

   1.3 Frequency Response: -3 db @ 0.5 Hz and 200 KHz

   1.4 Input Z: 1000 Meg shunted by 15 pf

   1.5 Output Z: 50 ohms

2. Post Amplifier

   2.1 Ithaco Model 454

   2.2 Voltage Gain: Variable -10 db to +90 db in 1 db steps

   2.3 Frequency Response: -3 db @ 1 Hz and 100 KHz

   2.4 Input Z: 1 Meg ohm shunted by 100 pf

   2.5 Output Z: 20 ohms maximum

3. Analog Filter

   3.1 Rockland Model 1100

   3.2 Band pass 10 Hz to 1.1 MHz selectable

   3.3 24 db per octave attenuation slope

   3.4 0 db insertion loss

4. Tape Recorder

   4.1 Sangamo Model 3614

   4.2 Seven speeds 1-7/8 ips to 120 ips

   4.3 Fourteen Data Channels & Two Edge Tracks

   4.4 Power: 30 ± 2V dc; 28.5 ± 1.9V dc; 24 ± 1.6V dc

4. Tape Recorder (Continued)

   4.5 Direct Record

      4.5.1 Frequency Response: 400 Hz to 600 KHz

      4.5.2 Input Signal Levels: 0.2 to 10 Vrms

      4.5.3 Input Impedance Levels: 75 ohm & 10,000 ohm

   4.6 F.M. Record

      4.6.1 Frequency Response: D.C. to 40 KHz

      4.6.2 Input Signal Level: 1 Volt rms nominal

      4.6.3 Input Impedance Levels: 75 ohm & 20,000 ohm

5. Visicorder

   5.1 Honeywell Model 2206

   5.2 12, 24, 28 VDC operation

   5.3 Record Travel Speeds: 0.02 to 80 ips

   5.4 12 Channels for Data plus 2 Event Channels

   5.5 Frequency Response: 0-25,000 Hz, dependent on galvonometer type

6. Signal Conditioning Amplifiers for Visicorder (Driver Amplifiers)

   6.1 Honeywell Accudata 112

   6.2 Gain: 1, 2, 5, 10, 20, 50, 100, 200, 500, & 1000 w 1/200 attenuator

   6.3 Frequency Response:

      6.3.1 With Attenuator: ±1 db from DC to 20 KHz

      6.3.2 Without Attenuator: ±5% from DC to 20 KHz

   6.4 Output Impedance: Less than 1 ohm

7. Digital Clock

   7.1 Sprengnether TS-200 Digital Timing System

   7.2 Input Synchronizes to 600 Hz Audio Tone from W.W.V.

      7.2.1 Voltage Range 100 MV to 1 V R.M.S.

   7.3 Outputs

      7.3.1 Nine cold cathode indicator tubes for visual

      7.3.2 Contact closures for second, minute, hour, and day for electrical

   7.4 Stability

      7.4.1 Aging: 1 part in 10^7 per day

      7.4.2 Line Voltage: ±5 parts in 10^7 maximum for 10% change

7. Digital Clock (Continued)

   7.5 Power Input

      7.5.1 12 VDC ± 10%

      7.5.2 120 or 240 VAC

8. Receiver

   8.1 Specific Products Model WVTR

   8.2 Operating Frequencies: 2.5, 5, 10, 15, 20, and 25 MHz

   8.3 Stability: ±2 KHz

   8.4 Type Reception: AM & MCW

   8.5 Audio Output: 16 ohms @ speaker & 100 ohms at output terminals

   8.6 Power

      8.6.1 9 VDC @ 100 MA

      8.6.2 Optional 120 VAC supply

9. Inverter

   9.1 Topaz Electronics Model 250GW-12-24-60

   9.2 Output Power: 250 Volt-Amps

   9.3 Input Power: 22-30 VDC @ 4-16 Amps

10. Batteries

   10.1 Yardney Electric Silvercel Model LR4/80

   10.2 80 Amp Hour Rating

   10.3 Nominal Voltage during Discharge 6.0V

   10.4 Nominal Voltage @ Full Charge 7.24V

   10.5 Nominal Voltage @ Full Discharge 5.2V

11. Motor Generator

   11.1 Homelite Model 11GA50-2 with Voltamatic & Loadamatic Control

   11.2 Output: 5000 Watts, 115 or 230 VAC. Single Phase

   11.3 Prime Power: Briggs & Stratton Model 243431, 4 cycle engine

12. Battery Charger

   12.1 Yardney Electric Model VC-24-10

   12.2 Line Input: 115 V ± 10%, 50-60 Hz

12. Battery Charger (Continued)

    12.3 Battery Charging Terminated Automatically when full capacity is reached

    12.4 Charge 1 to 24 cells in series

    12.5 Charging Current 0-10 Amps Variable

13. Walkie Talkies

    13.1 Motorola Inc. (Handie Talkie) HT 220 Series, Remote Speaker & Microphone Model

    13.2 Output Power: 5 Watts

    13.3 Frequency Modulated

    13.4 Operates in Business Band

14. Dodge Van, 1971

    14.1 B300 Series

    14.2 Gross Vehicle Weight: 7700 lbs.

    14.3 Wheelbase: 127"

    14.4 Usable Space: About 60" Wide x 44" High x 112" Long

15. Trailer

    15.1 Van Type, 4' Wide x 6' Long x 53" High

    15.2 Model LV built by Kar-Go Manufacturing of Akron, Ohio

    15.3 Gross Vehicle Weight about 1000 lbs.

16. Airconditioner

    16.1 Coleman 10,000 B.T.U.

    16.2 Starting Power 2500 Watts, 110 V @ 25 Amps

    16.3 Running Power 1300 Watts, 110 V @ 13 Amps

17. Transducer Cable Reel

    17.1 Model 5874-1 Portable Breast Reel

    17.2 Mark Products, Inc.

18. Special Cables

    A. Transducer Cable

    A.1 Alpha Wire Co., distributed by Loral Distributor Products

18. Special Cables (Continued)

A.2 Alpha #6010

A.3 Three Twisted pair of #22, each pair individually shielded; shields insulated from each other

A.4 Capacitance: 25 pf/ft. between conductors, 45 pf/ft. between a single conductor and shield

B. Microdot Cable

B.1 Microdot Inc. #250-3804

B.2 Coaxial 50 ohm cable

B.3 Characteristic Impedance 54 Ω

B.4 Capacitance 28.8 pf/ft.

C. Borehole Probe Cable

C.1 Rochester Corporation type 3N5-S

C.2 Three conductors plus shield

C.3 Resistance: .012 ohms/ft.

C.4 Breaking Strength: 200 lbs.

C.5 Weight: .068 lbs/ft.

19. Special Connectors

A. Transducer Cable

Amphenol MS-3106A-14S-6P

B. Preamplifier Input

Microdot #052-0213

C. Preamplifier Output

Amphenol MS-3116-F10-6S

20. Magnetic Recording Tape

20.1 14" Reels used on Sangamo tape recorder in van
3M Company Part No. 871-1-7200
7200 foot roll of 1 mil polyester base magnetic instrumentation tape

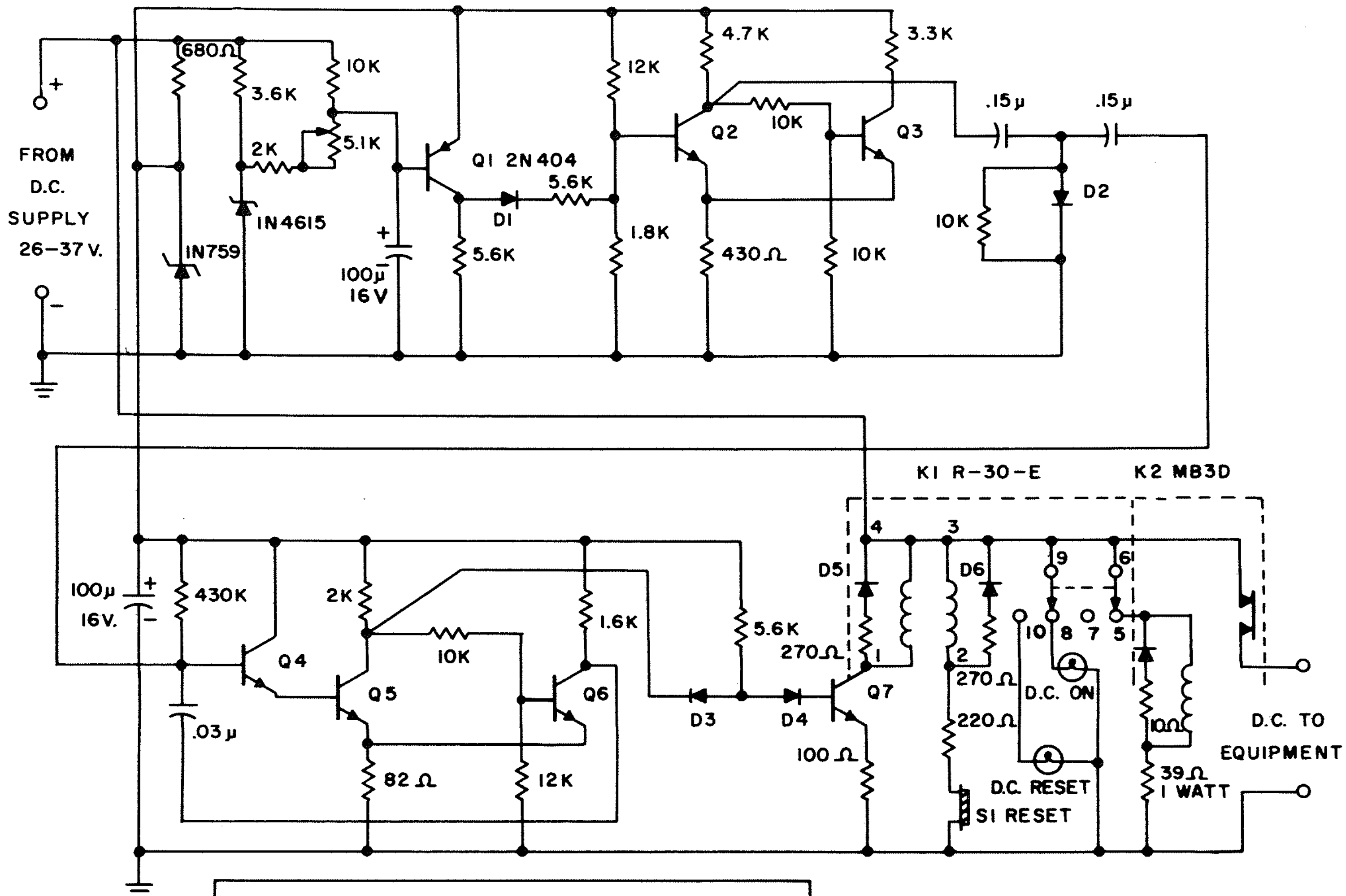
21. Visicorder Paper

21.1 Eastman Kodak Co. #1895 Instrumentation Paper; Specification #2
Emulsion Out; 6" Wide x 100' Long

APPENDIX B

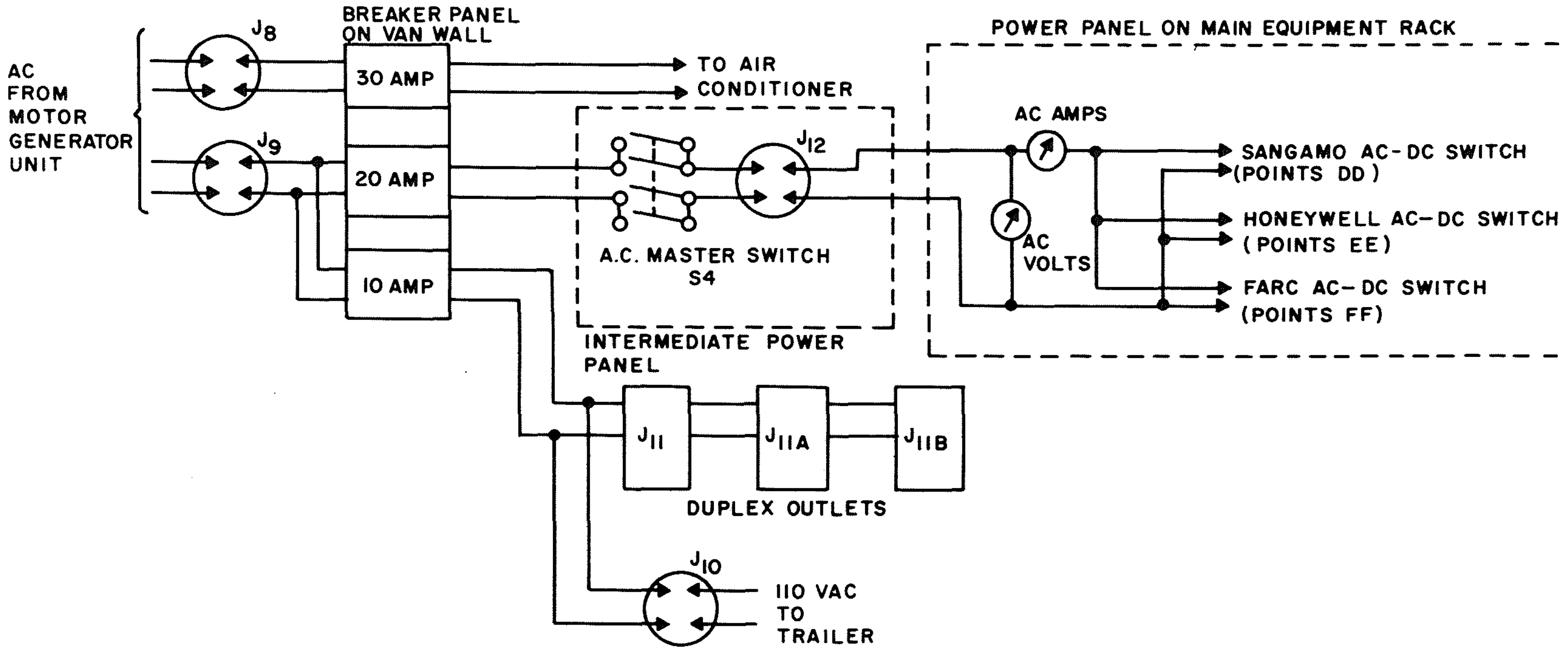
Circuit Diagrams of the AC and DC Power Systems

This appendix includes circuit diagrams associated with the AC and DC power systems in the van and trailer units of the mobile microseismic monitoring facility.



1. ALL RESISTORS 1/2 W ± 5% UNLESS NOTED
2. ALL TRANSISTORS 2N706 A. EXCEPT Q1
3. ALL DIODES IN458 A. UNLESS NOTED

Figure B1 - Circuit Diagram of Voltage Sensing Circuit



1. J_8 & J_9 : TI-123RM OUTSIDE VAN WALL
2. J_{10} : TI-123RF OUTSIDE VAN WALL
3. J_{11} & J_{11A} : DUPLEX OUTLET INSIDE VAN WALL
4. J_{12} : AMPHENOL MS3102A-20-24P LOCATED ON INTERMEDIATE POWER PANEL
5. J_{11B} : LOCATED IN RADIO STORAGE BOX
6. A.C. MASTER SWITCH LOCATED ON INTERMEDIATE POWER PANEL S4

Figure B2 - Overall Layout of AC Switching and Distribution Circuit

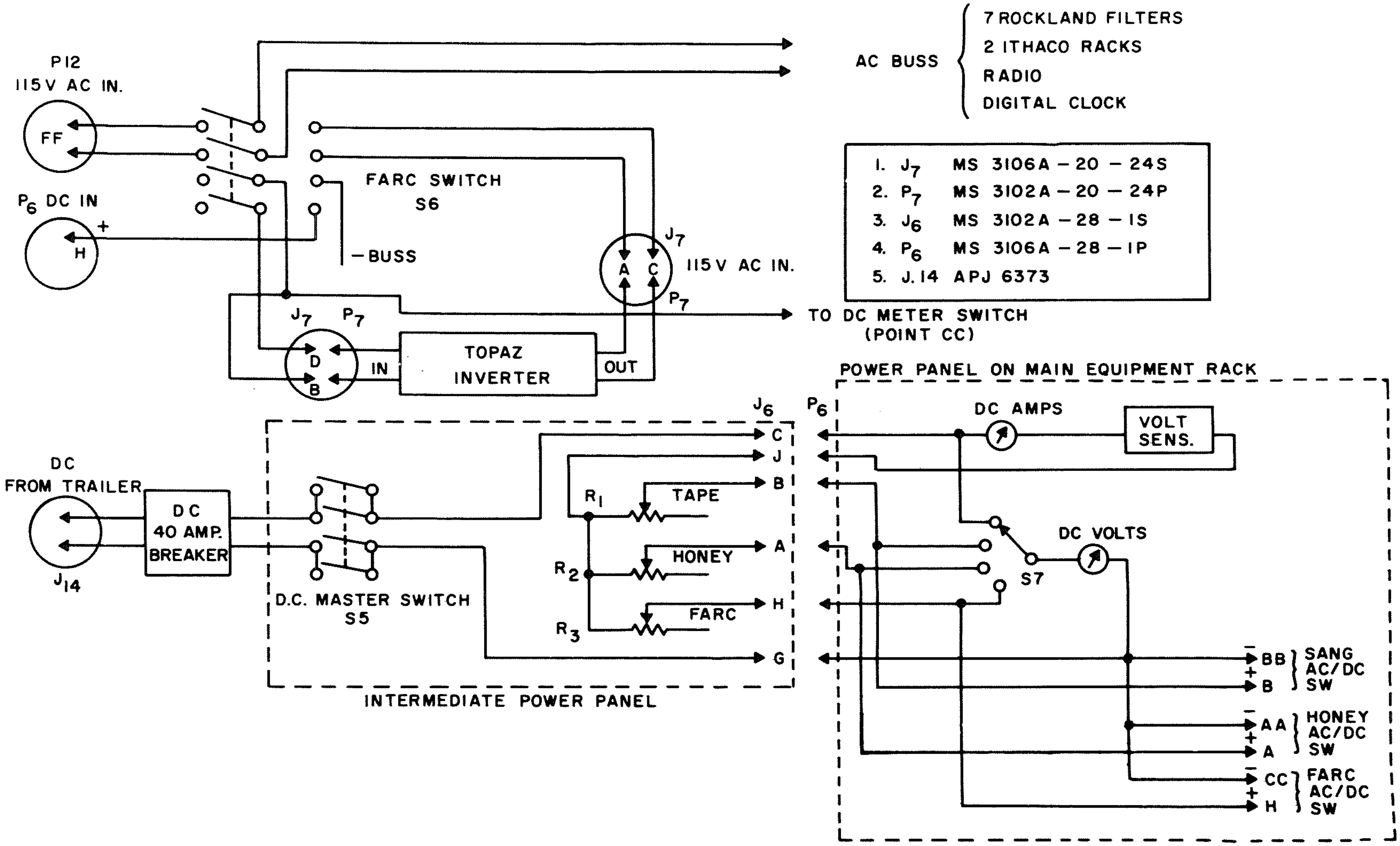


Figure B3 - Overall Layout of DC Switching and Distribution Circuit, and Inverter Circuit

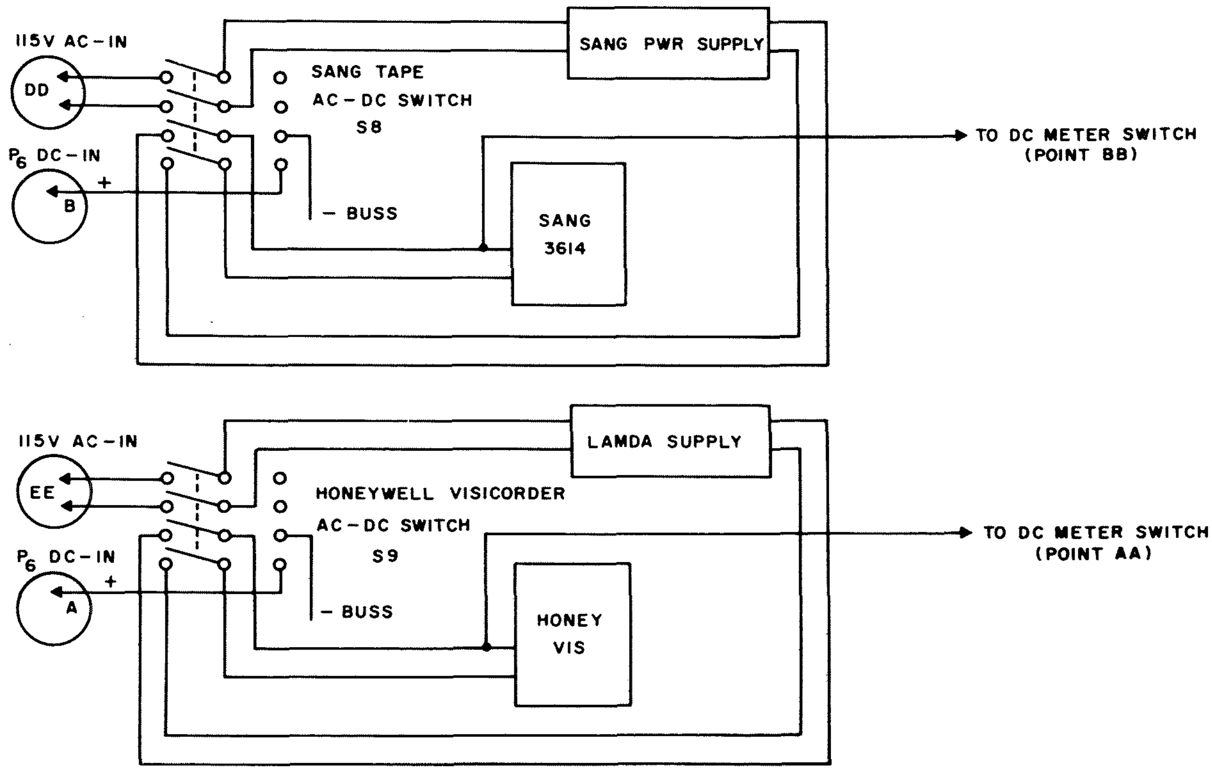


Figure B4 - AC/DC Switching Circuits for Magnetic Tape Recorder and UV-Recorder

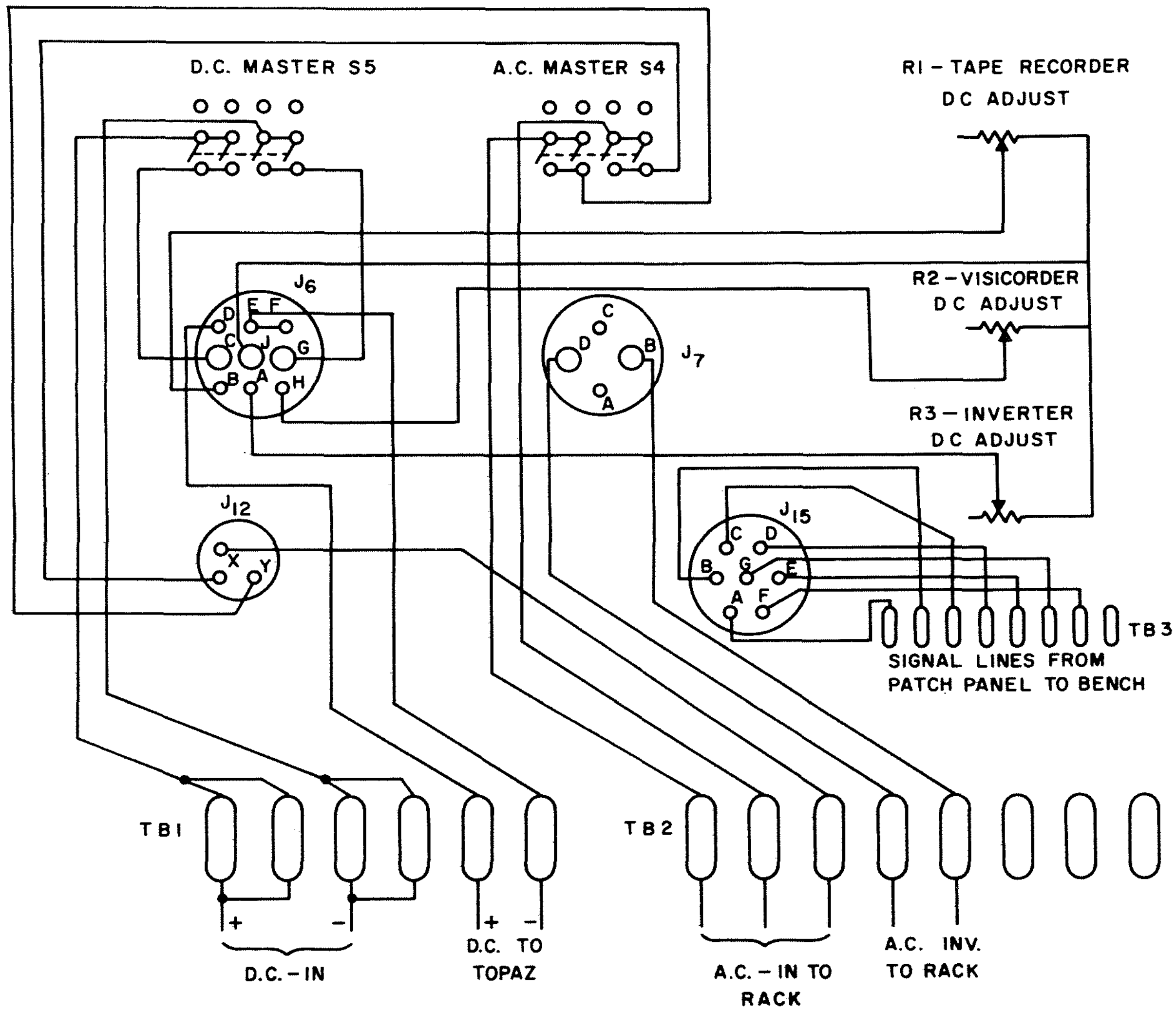


Figure B5 - AC and DC Wiring in Intermediate Power Panel

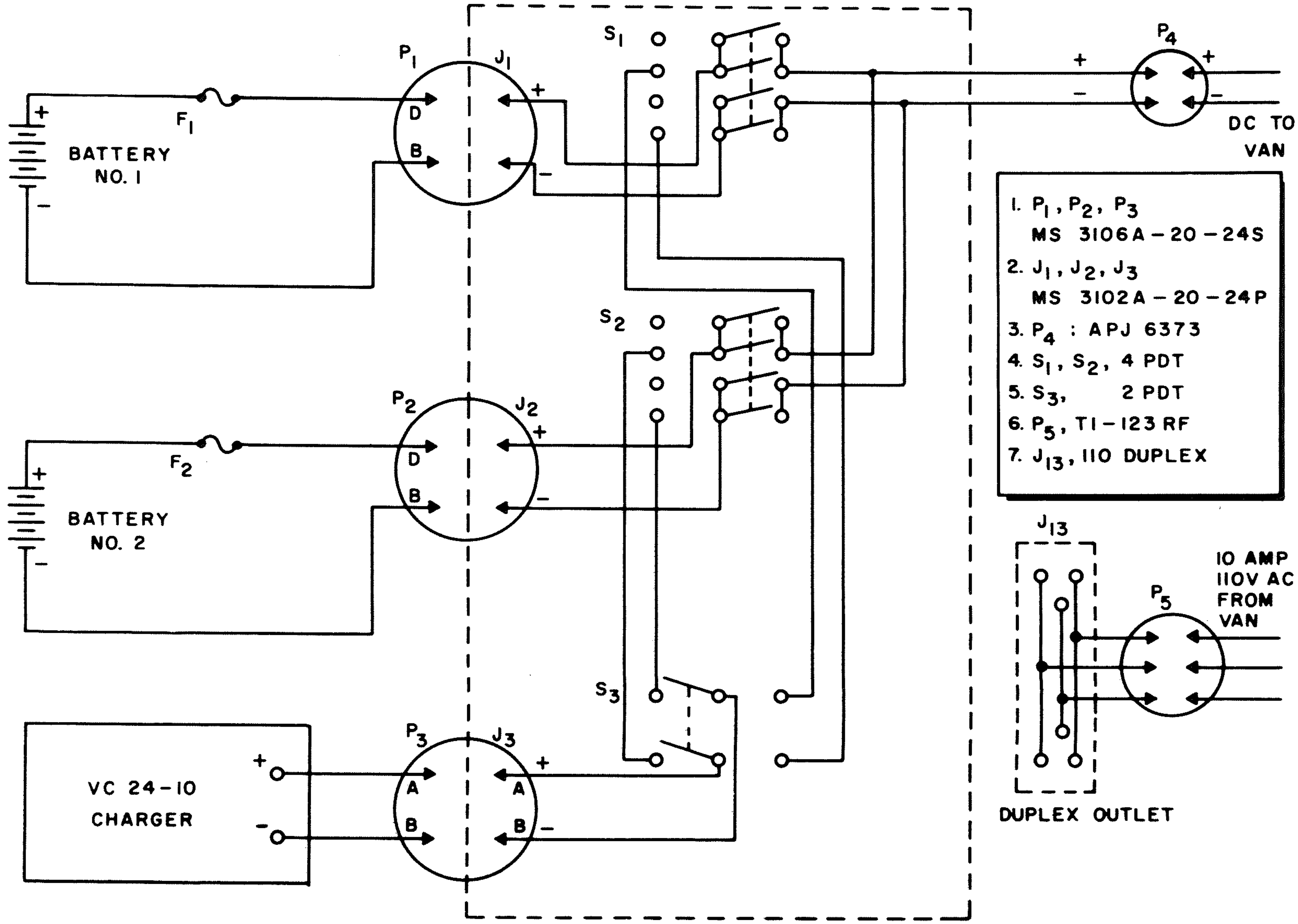


Figure B6 - Circuit Diagram of AC/DC Wiring in Trailer

APPENDIX C

Transducer Specifications

The purpose of this appendix is to present a brief review of the important specifications of the various basic transducers used during the current studies.

1. Geophones (Velocity Gages)

Geospace model GSC-11D geophones have been used extensively at Penn State and elsewhere for detection of microseismic activity. Figure C3 shows one of the basic geophone elements and a geophone packaged in a marsh-type case. This type of packaging has proven extremely satisfactory for long term stability under extremely high moisture conditions. The specifications for both the 8 Hz and 14 Hz geophones utilized are given below.

Specifications of Geospace GSC-11D Geophones

Natural frequency	8.0 Hz and 14.0 Hz ± 0.5 Hz
Standard coil resistance @ 25°C:	380 ohms ± 5%
Total moving mass:	.568 oz. (16.1 grams)
Intrinsic voltage sensitivity with 380 ohm coil:	0.81 volts/in/sec (0.32 volts/cm/sec)
Intrinsic power sensitivity:	1.73 mw/in/sec
Voltage/weight ratio:	.213 volts/in/sec/oz
Power/weight ratio:	.44 mw/in/sec/oz
Normalized transduction constant:	$.042 \sqrt{R_c} \pm 5\%$
Harmonic distortion:	Less than 0.2% with a driving velocity of 0.7 in/sec (1.8 cm/sec) peak-to-peak
Maximum coil excursion:	0.10 inch p-p (.25 cm p-p)
Damping constant with 380 ohm coil:	617 (8 Hz) 353 (14 Hz)

Specifications of Geospace GSC-11D Geophones (Continued)

Dimensions-Basic Unit

Height:	1.32" (3.36 cm)
Diameter:	1.25" (3.18 cm)
Weight:	3.9 oz. (111. gm)

Dimensions-Marsh Case

Height:	4.75" (excluding 3" spike)
Diameter:	1.75"

Ordering Details: Type GSC-11D
Model M-4
Case Type PC-25
Spike Type S-10

Typical response curves for both 8 and 14 Hz geophones are presented in Figures C1 and C2. In most cases the geophones are operated with an external shunt resistor located in the associated transducer junction box. Shunt resistors of 5.1K and 910 ohms are normally employed with the 8 Hz and 14 Hz units respectively. As indicated in Figures C1 and C2 the sensitivity of both geophone models drops rapidly at frequencies below their natural frequency. At frequencies above the natural frequency, however, their sensitivity remains relatively constant (after a slight initial drop in sensitivity above the natural frequency). The manufacturer does not provide sensitivity data above a few hundred Hz however, experience by other workers has indicated that the sensitivity of these type of geophones remain relatively flat up to frequencies of the order of 2000-3000 Hz.

2. Accelerometers

In recent studies at Penn State accelerometers have been mainly used as sensing elements in the borehole probe unit, although in early experiments (in a local quarry) they were bonded directly to rock surfaces. Two different accelerometers have been utilized, namely Endevco models 2219E and 2233E as

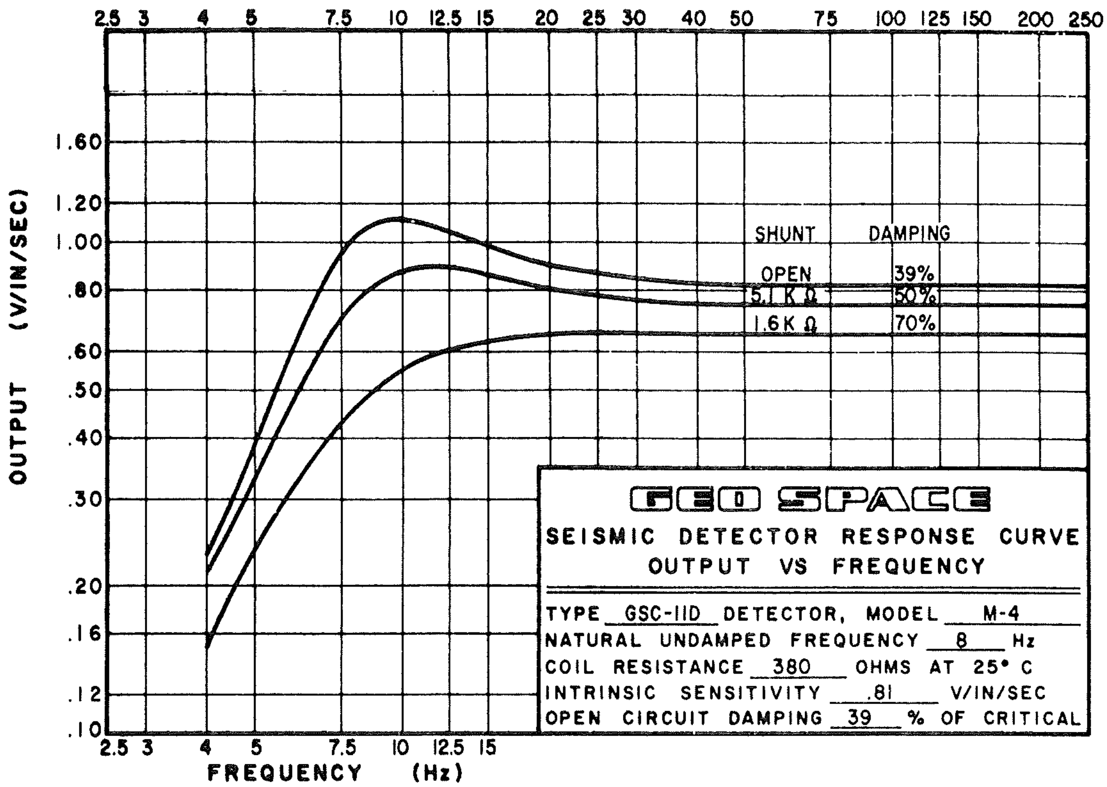


Figure C1 - Frequency Response Curves for Geospace Type GSC-11D, Model M-4, 8 Hz Geophone

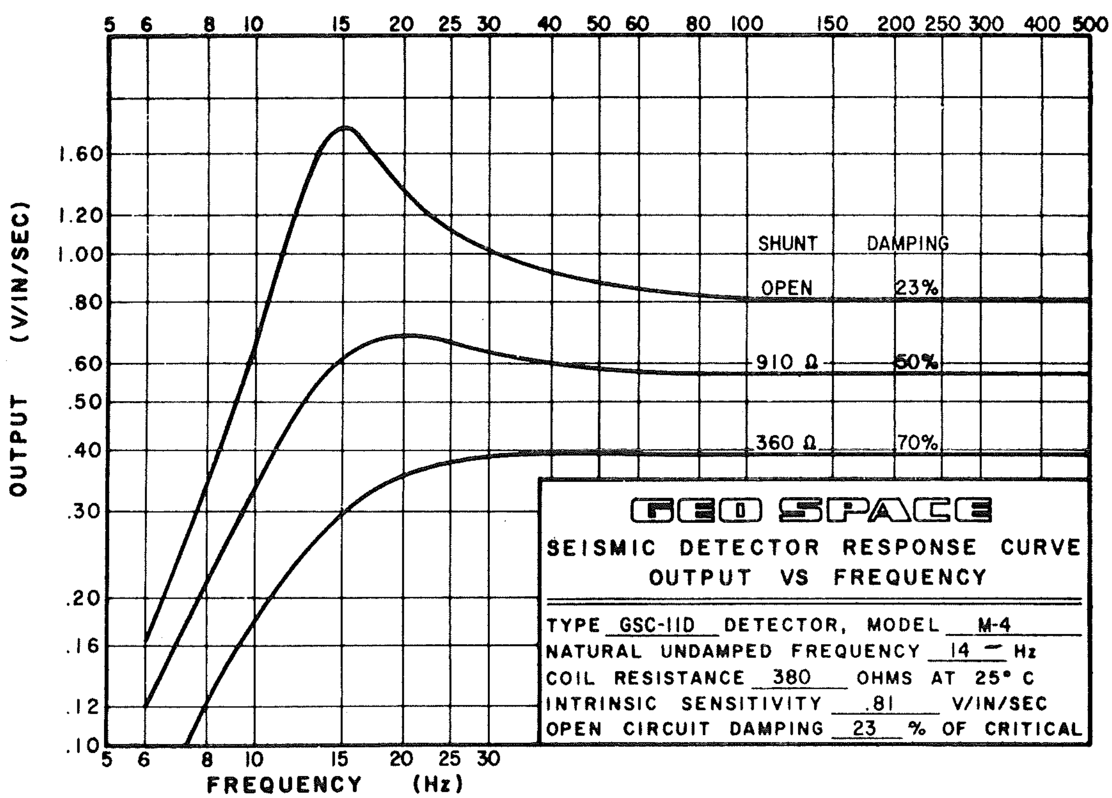
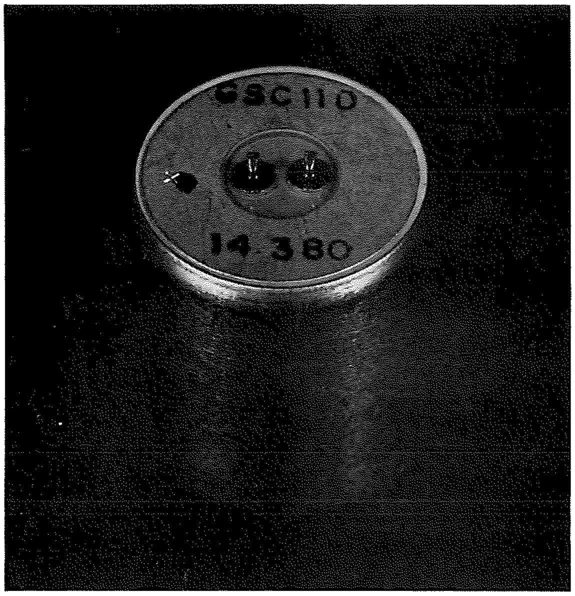
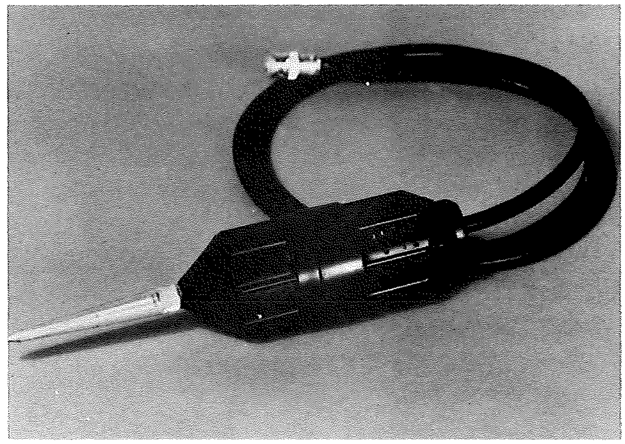


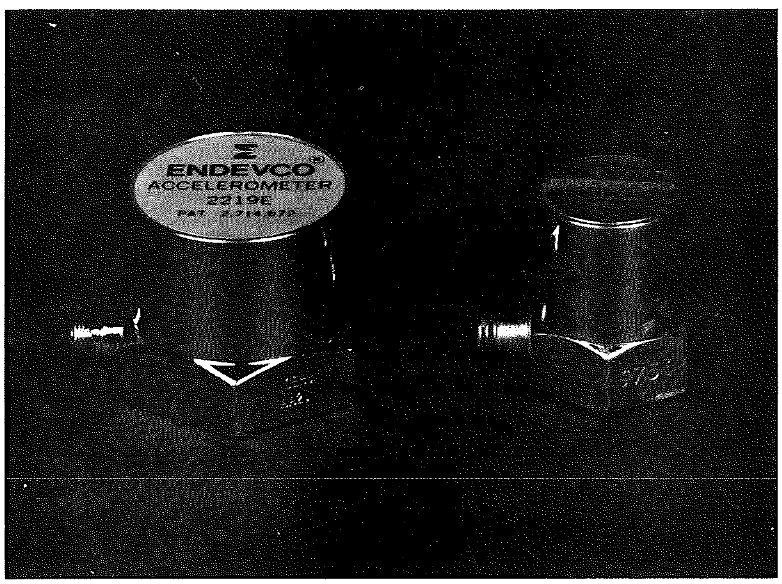
Figure C2 - Frequency Response Curves for Geospace Type GSC-11D, Model M-4, 14 Hz Geophone



(A) Basic Geophone Element



(B) Geophone in Marsh Case



(C) Accelerometers
[LHS-Model 2219E, RHS-Model 2211C (similar indesign and dimensions to model 2233E)

Figure C3 - Geophones (Velocity Gages) and Accelerometers Used for Detection of Microseismic Activity shown in Figure C3. The specifications for these two models are listed and typical response curves are shown in Figure C4.

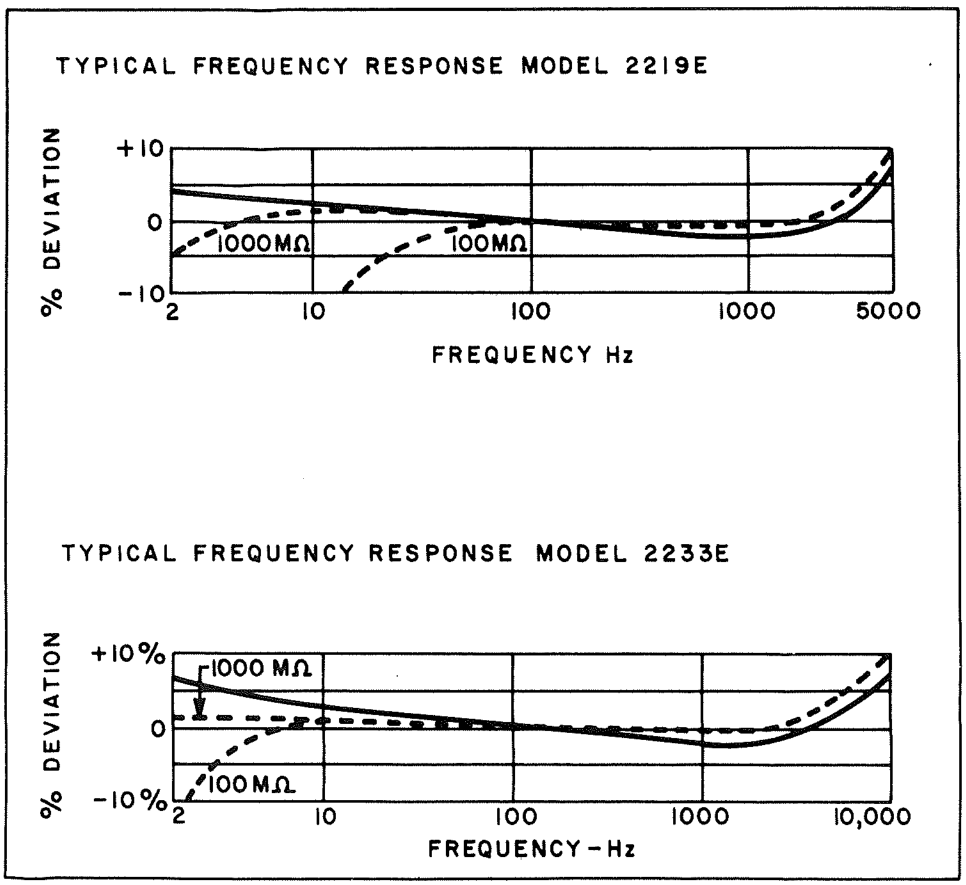


Figure C4 - Typical Response Curves for Endevco 2219E and 2233E Accelerometers [Solid curves are charge-frequency response, broken lines are voltage-frequency response with loads shown and 100 pF external capacitance]

(A) Specifications of Endevco Model 2219E Accelerometer

Charge sensitivity:	85 pC/g, ±20%
Voltage sensitivity*:	370 mV/g, nominal
Mounted resonance frequency:	16,000 Hz, ±10%
Frequency response (±5%):	Charge: 2 to 3000 Hz, nominal Voltage: 20 to 3000 Hz, nominal+
Transverse sensitivity:	5% max.
Amplitude linearity, range:	Sensitivity increases approximately 1% per 25 g, 0 to 100 g.
Resistance:	20,000 MΩ, min. at +75°F
Transducer capacitance:	135 pF, nominal
Design:	Isolated compression
Weight:	72 grams (2.6 oz.)
Height:	0.81 in.
Width:	0.938 in. HEX.

(B) Specifications of Endevco Model 2233E Accelerometer

Charge sensitivity:	60 pC/g, nominal
Voltage sensitivity*:	45 mV/g, nominal
Mounted resonant frequency:	32,000 Hz, nominal
Frequency response (±5%):	Charge: 4 to 8000 Hz, nominal Voltage: 4 to 6000 Hz, nominal+
Transverse sensitivity:	3% max.
Amplitude linearity:	Sensitivity increases approximately 1% per 150 g, 0 to 1000 g.
Transducer capacitance:	1000 pF, ±20%
Resistance:	20,000 MΩ, min. at +77°F (+25°C)
Design:	Single-ended compression
Weight:	32 grams (1.2 ounces)
Height:	0.79 in.
Width:	0.63 in. HEX

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* With 300 pF/external capacitance

+ With 100 MΩ load

APPENDIX D

Field Studies at Local Sites

Two local field sites were selected for initial trials on the microseismic monitoring system, namely:

Site A - A road cut within the Borough limits of State College, Pennsylvania (Easterly Parkway, near University Drive).

Site B - An abandoned section of the Neidigh Bros. Limestone Quarry, near Oak Hall, Pennsylvania.

At these sites a variety of microseismic transducers were installed using different techniques, and the response of these transducers and the operation of the monitoring system in general was evaluated. In these studies microseismic sources were simulated by impacting the rock strata using a sledge hammer and a Schmidt Hammer unit. Figure D1 shows the Schmidt hammer unit utilized.

The most detailed study was conducted at Site B shown in Figure D2. Here a variety of transducers were located at a fixed position on the edge of a rock face and hammer impacts were generated on the face at positions 10, 20 ..., 50 feet from the transducer location. Figure D3 shows a sketch of the test face at site B illustrating the locations of the various transducers and the impact locations, as well as a simplified block diagram of the monitoring system used. During field monitoring the filters (see Figure D3(B)) were set to provide a band pass of 10Hz - 50KHz.

Figure D4 shows signals obtained using the Schmidt hammer at position 1 monitored by an accelerometer attached to the rock surface. The Schmidt hammer is seen to generate remarkably reproducible signals at each blow. Figure D5 shows the signals monitored by four different transducer arrangements using a Schmidt Hammer blow at position 1 (10 feet away from the transducer location). The signals from the accelerometers which were mounted on a short length of

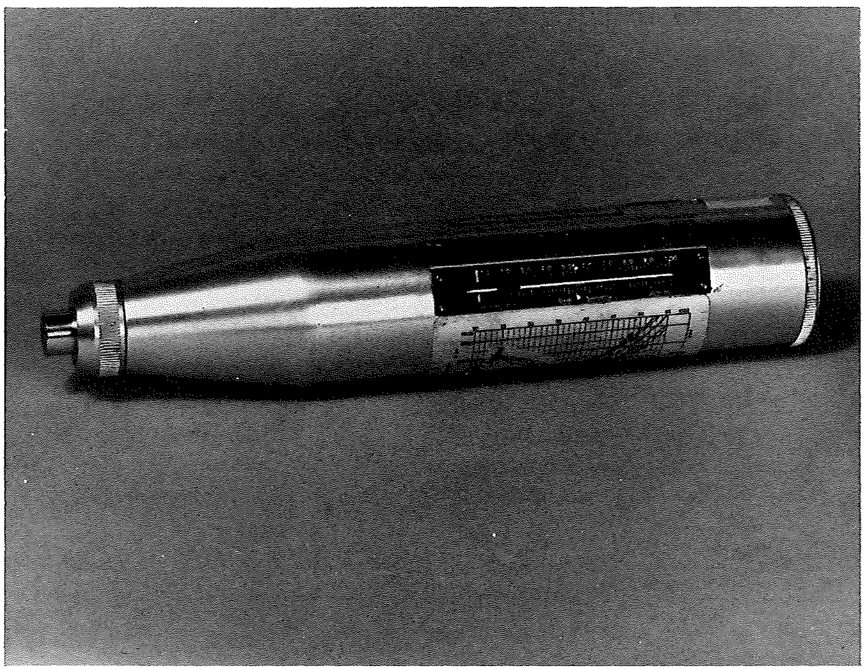
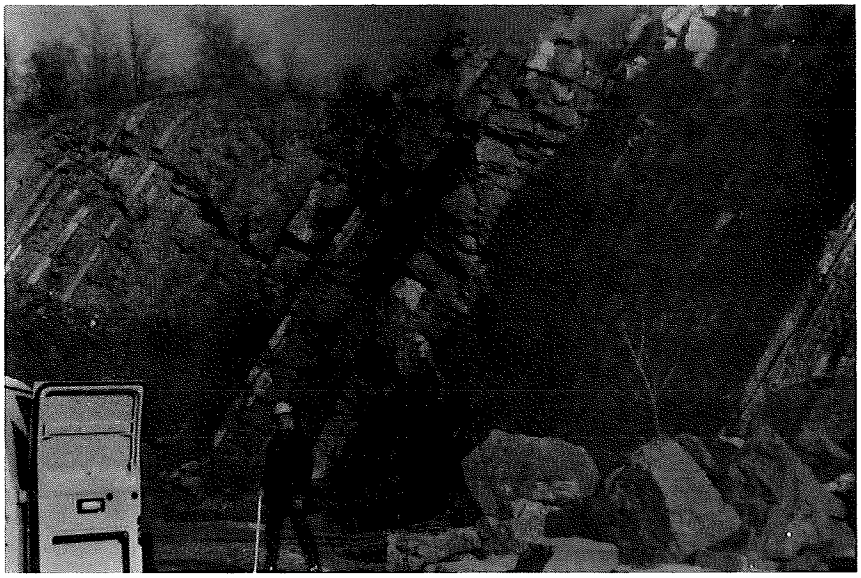
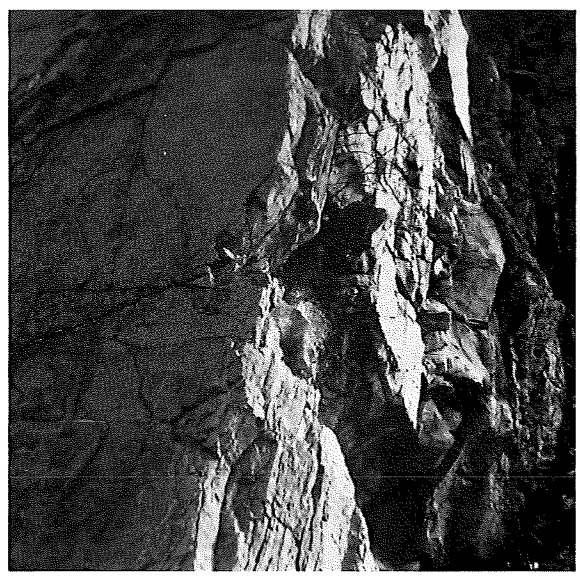


Figure D1 - Schmidt Hammer Unit



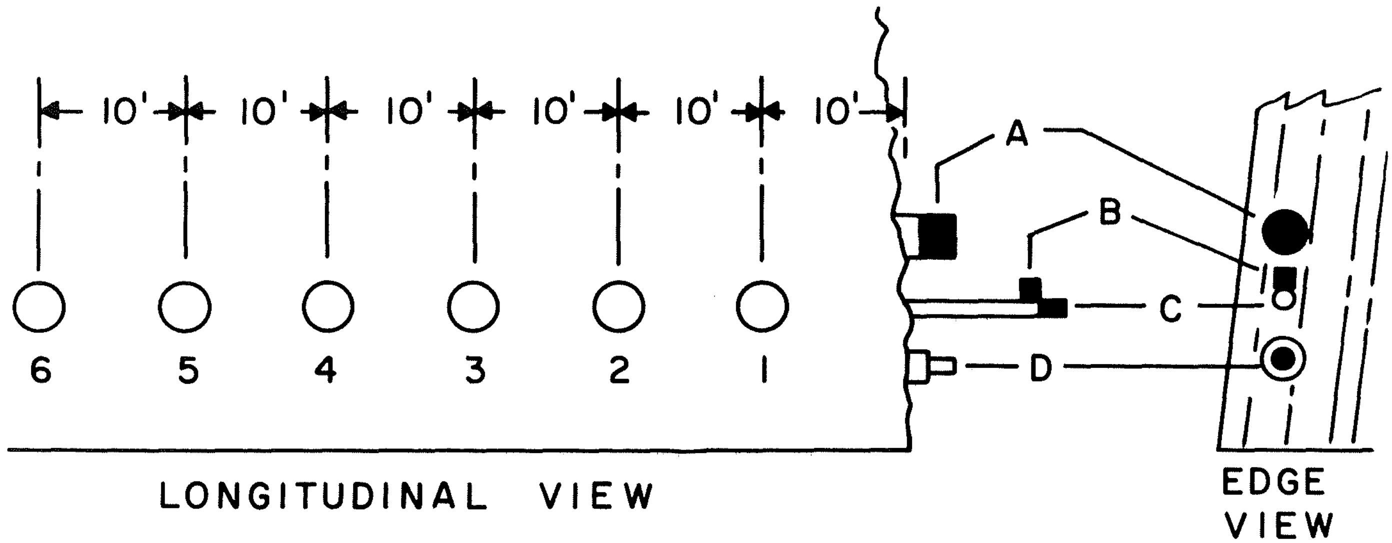
(A) Overall View of Quarry Area Utilized for Tests

(B) Mobile Facility at Test Site

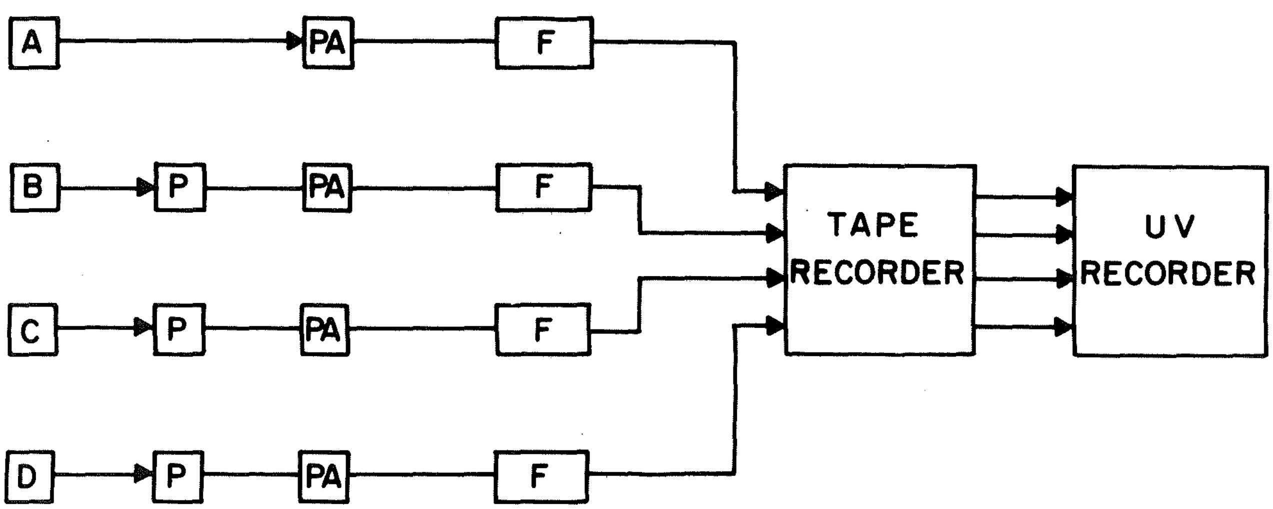


(C) Edge of Quarry Face Near Transducer Location

Figure D2 - Number of Views at Local Test Site B (Limestone Quarry)

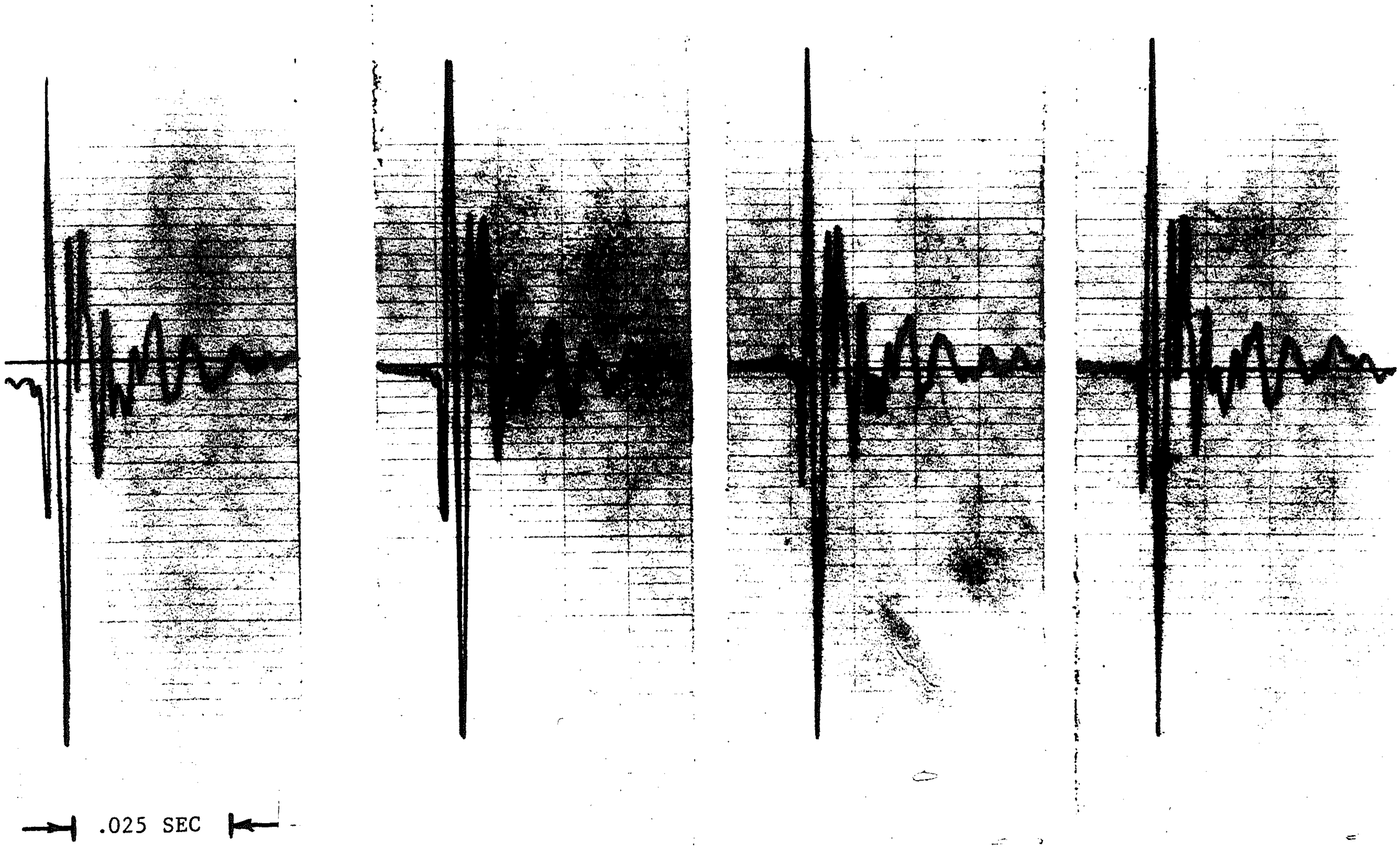


(A) Sketch of Test Face at Site B
[1-6 are impact locations, A is a geophone cemented to the rock, B and C are vertical and horizontal accelerometers mounted on steel pipe, D is accelerometer mounted to the rock]



(B) Monitoring System
[A-D are transducers described in (A) above, P are preamplifiers, PA are post amplifiers and F are filters]

Figure D3 - Experimental Arrangements at Test Site B for Evaluation of Preliminary Monitoring System



BLOW 1 BLOW 2 BLOW 3 BLOW 4

Figure D4 - Schmidt Hammer Blow at Position 1 (10 feet from Transducer) Monitored by Accelerometer Attached to a Brass Plate Bonded Directly to Rock Surface [Recording speed 60 in./sec., playback speed 60 in./sec., visicorder speed 40 in./sec., bandwidth 10-50,000 Hz, time scale 0.025 sec./in. as noted above]

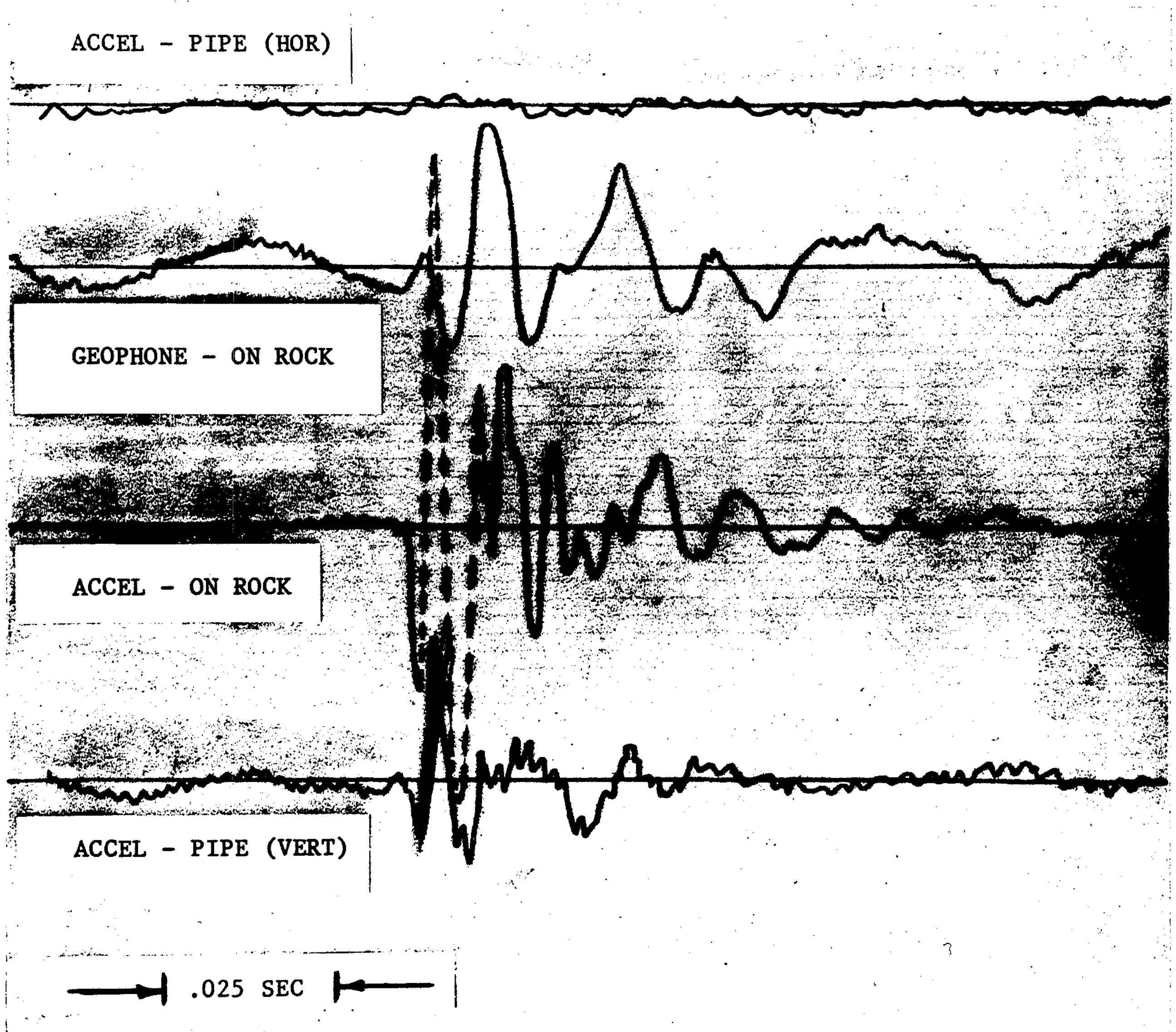


Figure D5 - Typical Signals Monitored by Various Transducer Arrangements
[Same test conditions as for data in Figure D4]

pipe (B,C) were found to be of a low level. This is probably due to poor coupling between rock and pipe. Improvement could be expected with the use of suitable grouting. As was expected the most sensitive arrangement was the accelerometer bonded directly to the rock surface.

Following a period of field recording the associated magnetic tapes were analyzed in the laboratory by playing them back through various filter arrangements to a UV-recorder. Figure D6 illustrates the amplitude-frequency data for background noise obtained using the geophone (A) and the accelerometer (D) which were both cemented directly to the rock. During the analysis the low frequency cutoff in the bandpass filter was subsequently increased while the high pass cutoff frequency was fixed at 20,000 Hz. The amplitude shown represents the maximum peak-to-peak value detected over a period of time and is in terms of inches of recorder chart (UV-recorder).

The background noise level in the geophone appeared to be greater than in the accelerometer, particularly in the lower frequency range. For both transducers the dominant frequency components of background noise were found to be below 200 Hz. In general the amplitude-frequency characteristics observed will naturally depend on the character of the test site and the degree of local cultural activity.

Following the analysis of background noise the attenuation of signals generated from impacts at the various locations was investigated. Table D1 shows the spectrum analysis of signals obtained from the bonded accelerometer (D) and the geophone (A) using a Schmidt Hammer at positions 1, 2, 3, and 4. The values presented are the average of five blows at each position. The symbol NS in the table indicates that certain of the impact signals were not separable from the background noise. Figure D7 shows the change of signal level with distance from the transducer location of three different filter

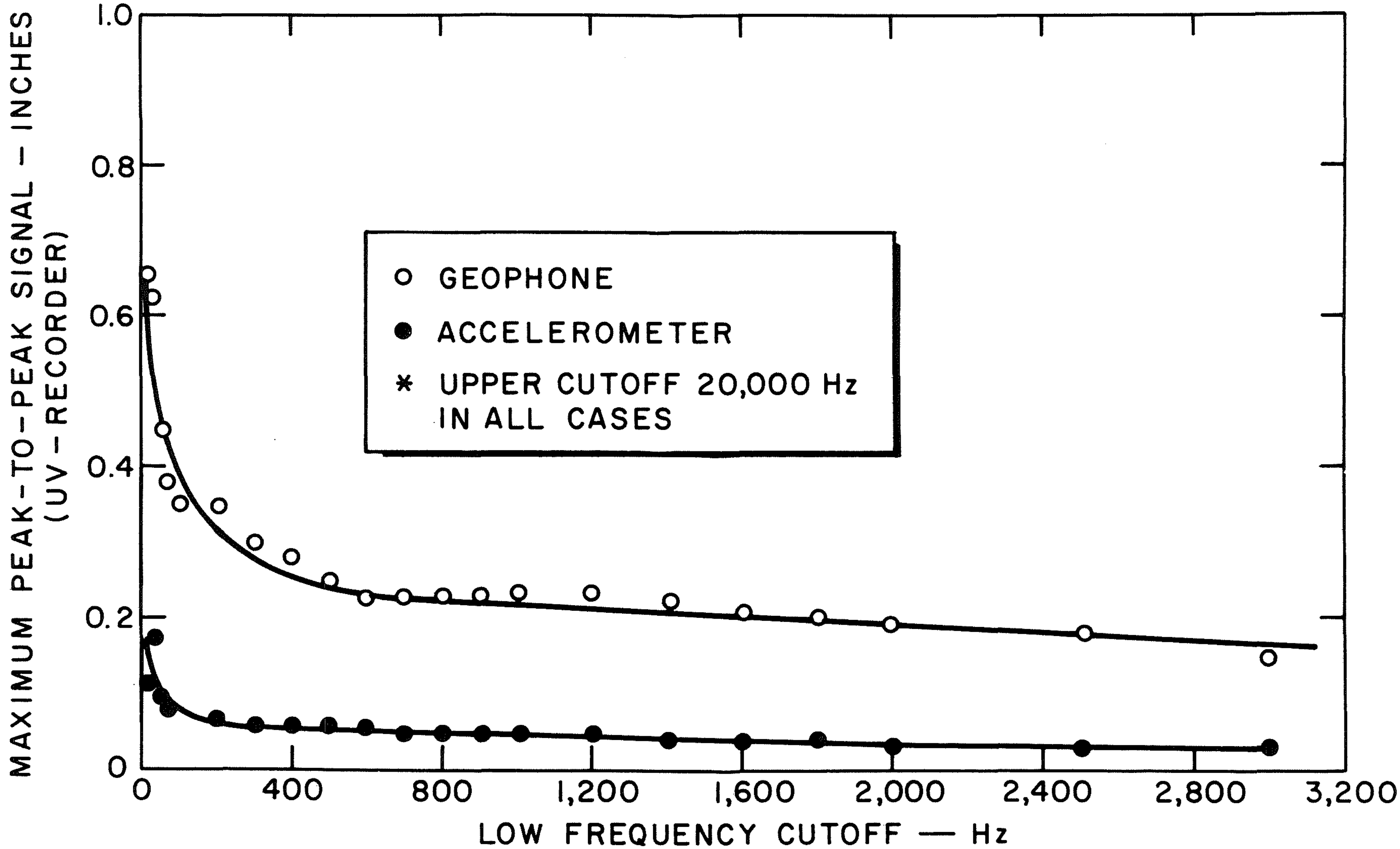


Figure D6 - Amplitude Versus Frequency for Background Noise at Field Site B

TABLE D1

Frequency Spectrum of Signals Obtained with Schmidt Hammer Blow at Position 1, 2, 3 & 4
(Recording Speed 60 in/sec, Playback speed 60 in/sec Unexpanded Signals)

Filter Bandwidth Hz	Maximum Peak-to-Peak Signal in Inches on UV-Recorder							
	Position 1*		Position 2		Position 3		Position 4	
	Accel.	Geophone	Accel.	Geophone	Accel.	Geophone	Accel.	Geophone
10-20,00	4.40	1.54	1.78	0.82	0.45	NS	0.10	NS
10-100	0.34	0.66	0.20	0.41	NS	NS	NS	NS
100-200	1.27	1.05	0.72	0.57	0.22	0.18	0.07	0.02
200-300	2.03	0.61	0.49	0.27	0.16	0.08	0.04	--
300-400	2.18	0.20	0.62	0.10	0.15	0.04	0.05	--
400-500	1.61	0.16	0.73	0.09	0.21	--	0.06	--
500-600	1.03	0.12	0.74	0.07	0.20	--	0.06	--
600-700	0.62	0.08	0.78	0.05	0.16	--	0.04	--
700-800	0.45	0.06	0.64	--	0.08	--	0.02	--
900-1,000	0.30	--	0.22	--	0.02	--	--	--
1,400-1,500	0.09	--	0.05	--	--	--	--	--
1,900-2,000	0.03	--	0.03	--	--	--	--	--
2,400-2,500	0.03	--	0.02	--	--	--	--	--

* - Denotes impact positions as shown on Figure D3(A).

NS - Denotes that signal from Schmidt Hammer impact is not separable from background noise.

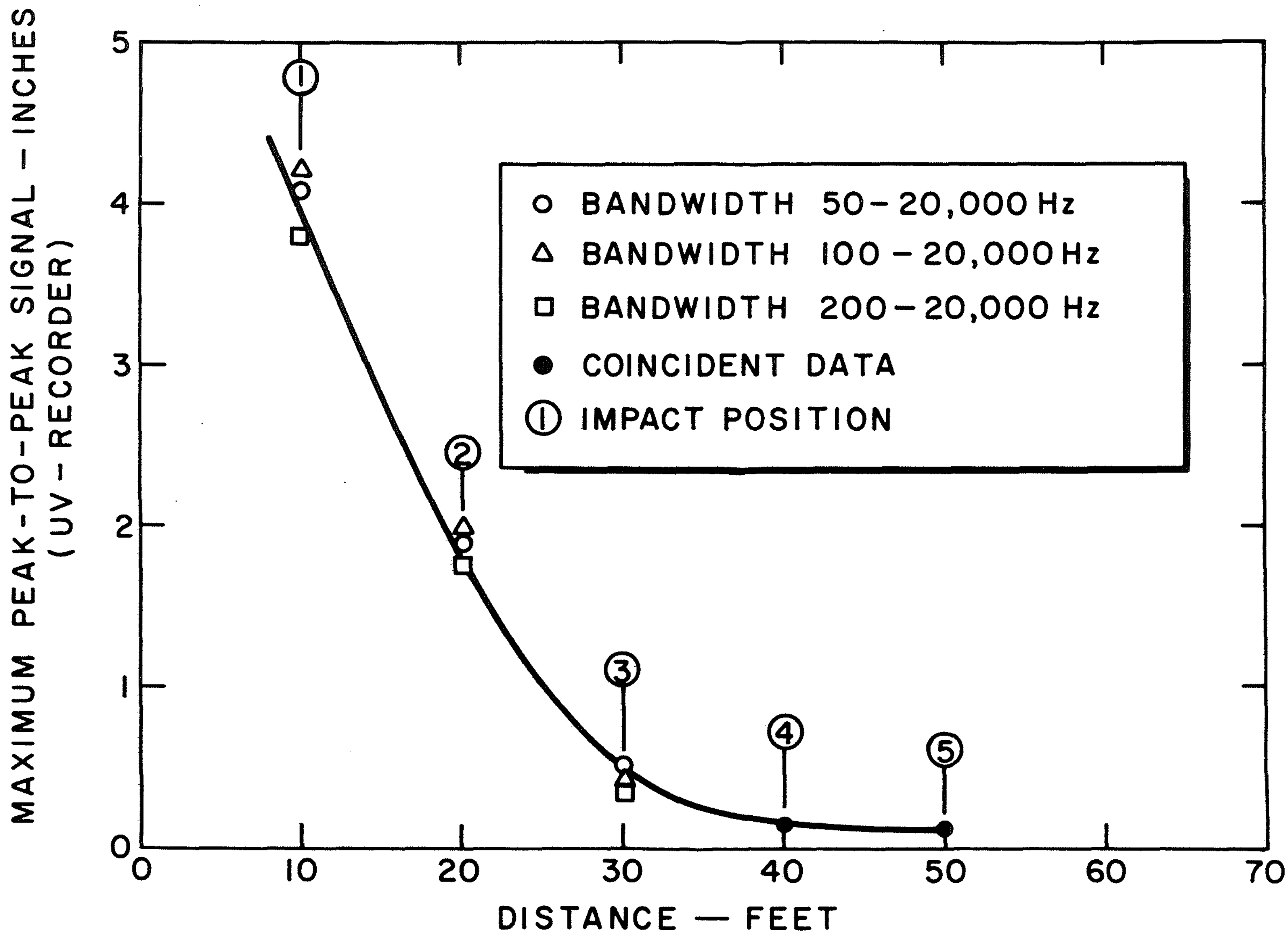


Figure D7 - Amplitude Versus Distance from the Transducer Location for Signals Generated by Schmidt Hammer Impact [Average of five impacts at each location, accelerometer transducer] band widths, 50-20,000 Hz, 100-20,000 Hz and 200-20,000 Hz. It is apparent that the signal level decreased rapidly with increasing distance but remained near the same level with increasing low pass cutoff frequency up to 200 Hz (for a fixed high pass cutoff frequency of 20,000 Hz).

The frequency spectrum of the signals generated using the Schmidt Hammer at positions 1 and 2 is presented in Figure D8. The signals were expanded and the amplitude was taken as the peak-to-peak value of the first cycle of the signal. The data presented are the average of two blows. Figure D9 shows the frequency spectrum of the unexpanded signals at position 1 over a wider frequency range (0-2500 Hz). In general the highest dominant frequency components are found to be slightly different at each position, however the dominant frequency components in general fall in the range of frequency 100-600 Hz in these tests.

The results of the preliminary tests presented here suggested that the seismic activity generated using the Schmidt Hammer could be effectively detected with the apparatus and technique developed. The most effective detection technique was an accelerometer mounted directly to the rock surface. The advantages of accelerometer over the geophone employed in this test was considered to be the capability of broad band response, high sensitivity, and low background noise. The most effective setting of the low pass cutoff frequency in the bandpass filter appears to be at 200 Hz. Under these conditions a low level signal could be easily identified from the background noise, that is there was a good signal-to-noise ratio.

Field site B was found to be a most useful site for preliminary field testing of microseismic monitoring facilities, and development of field techniques. During the late Spring and early Summer of 1972 this site was again utilized, this time for preliminary field trials on the microseismic

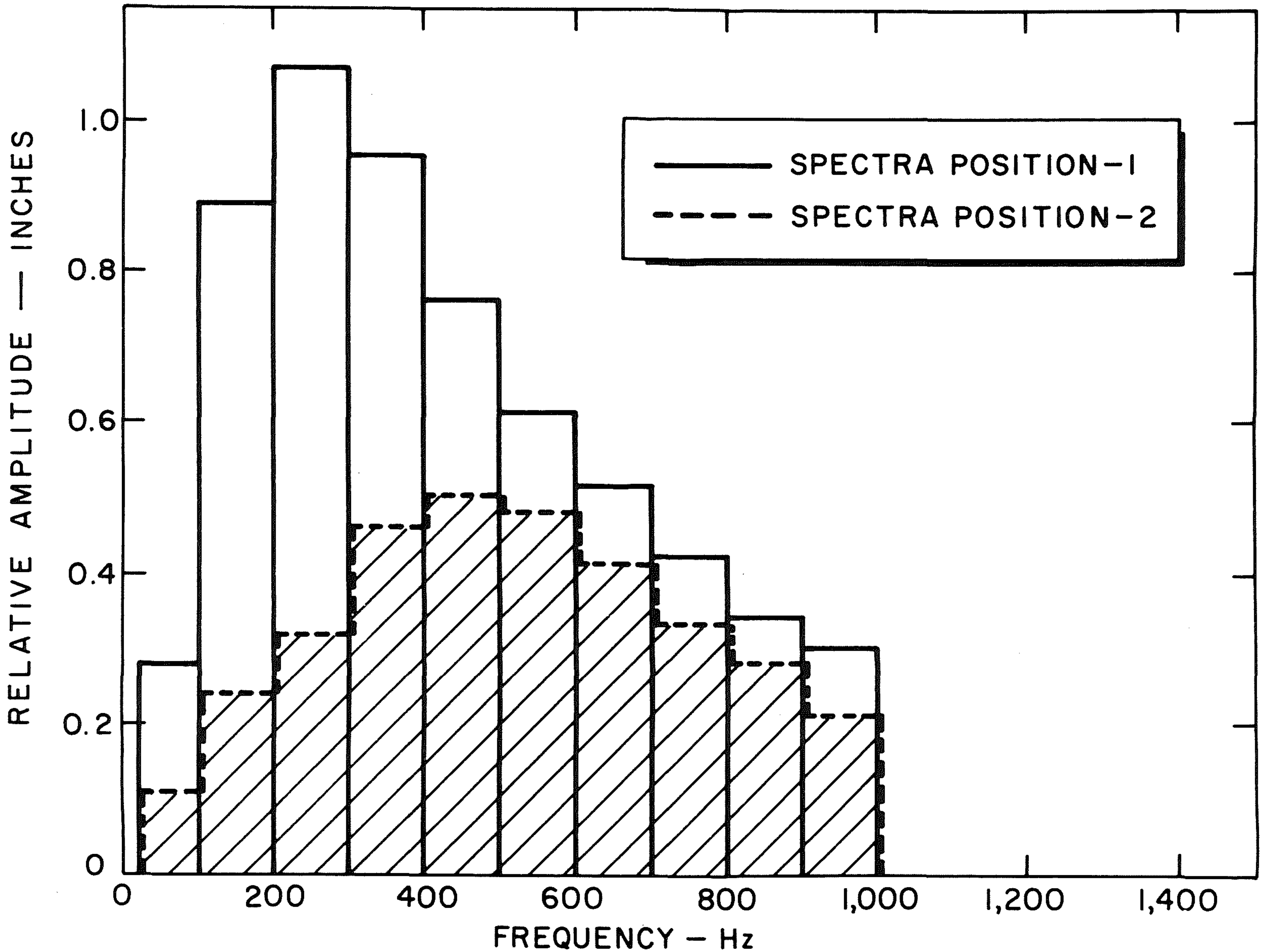


Figure D8 - Amplitude Versus Frequency for Schmidt Hammer Blows at Various Positions - Expanded Signal
[Average of two impacts, peak-to-peak amplitude of first cycle]

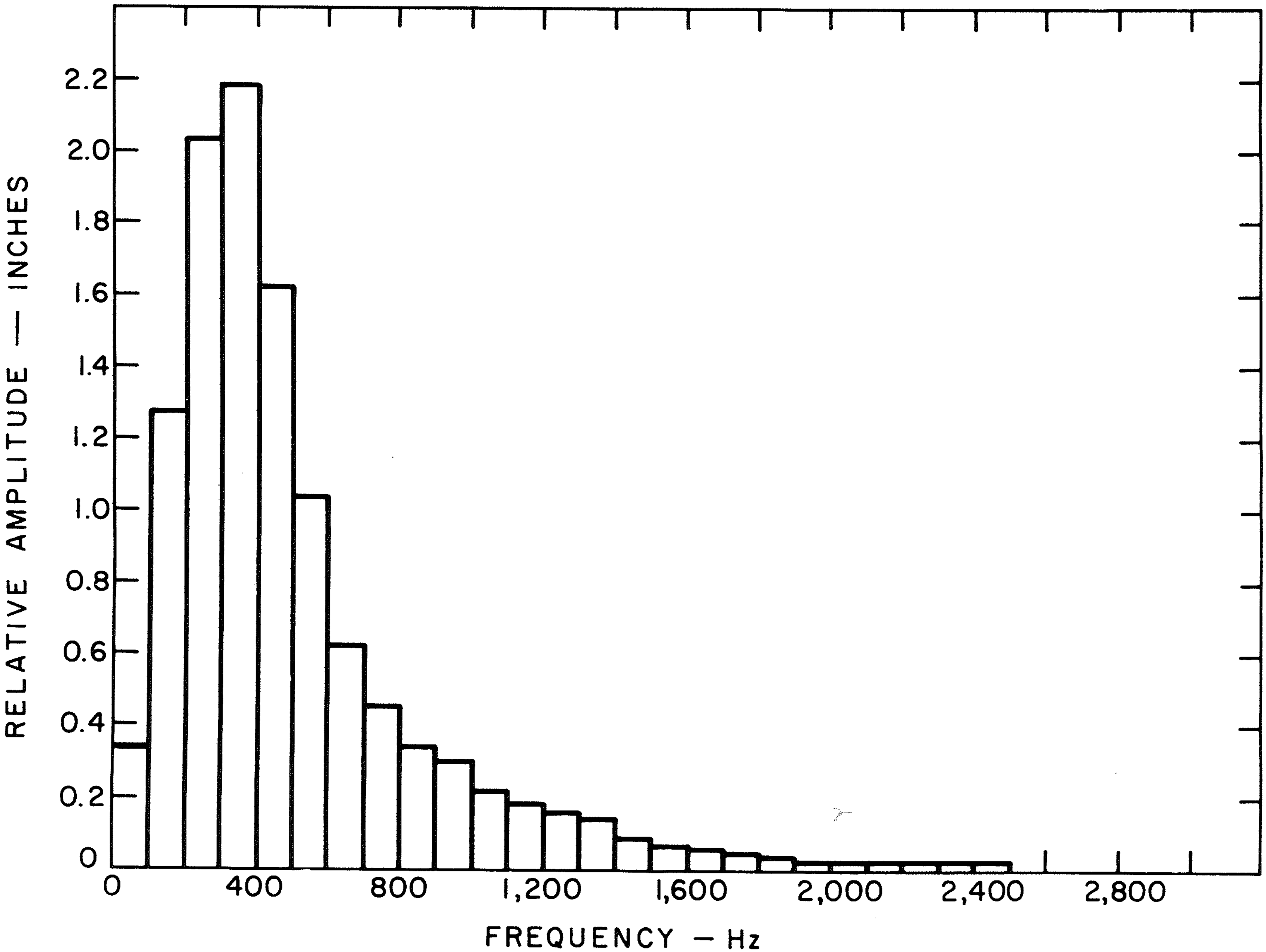


Figure D9 - Amplitude Versus Frequency for Schmidt Hammer Blows at Position 1 - Unexpanded Signal
[Average of two impacts, peak-to-peak amplitude of first cycle]

borehole probe being developed by the Department of Mineral Engineering for use on a number of microseismic field studies (including the current USBM project).

APPENDIX E

Physical Properties of Greenwich Mine Rock

1. General

As a minor part of the project, studies were undertaken to establish routine procedures and facilities for determining a number of mechanical properties of coal measure rocks. In particular methods for determining velocity and attenuation characteristics of these materials have been investigated. A limited number of tests were also carried out to determine the elastic moduli and uniaxial compressive strength of these materials. This appendix includes a brief review of these studies and includes physical properties of a number of rock types from the Greenwich mine.

2. Ultrasonic Properties

2.1 Initial Tests

Methods for determining velocity and attenuation characteristics of coal measure rocks under laboratory conditions have been investigated during this project (Kim [47]). An initial series of tests (Kim [48]) were completed on unstressed specimens using the test arrangement shown in Figure E1.* A pulse generator, which had a short rise time, triggered the transmitting crystal and the upper beam of the oscilloscope simultaneously. Barium Titanate crystals, having a resonant frequency of 200 kHz, were attached to each end of the cylindrical rock specimen (diameter 1-1/8 inches) to act as a transmitter and receiver pair. Figure E2 shows a photograph of the test arrangement, and details of the electronic equipment used are given in Appendix G.

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* It should be noted that this arrangement does not yield exact values of the bulk or dilatational velocity of the rock because the wave length of the pulse used is of the same order as the diameter of the specimen.

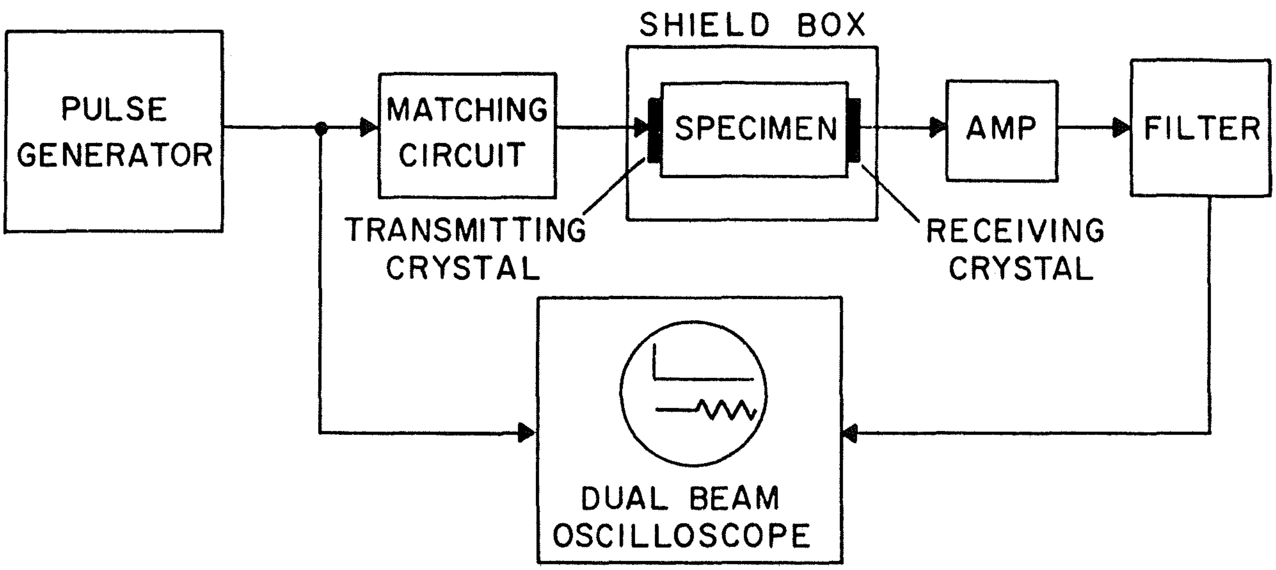
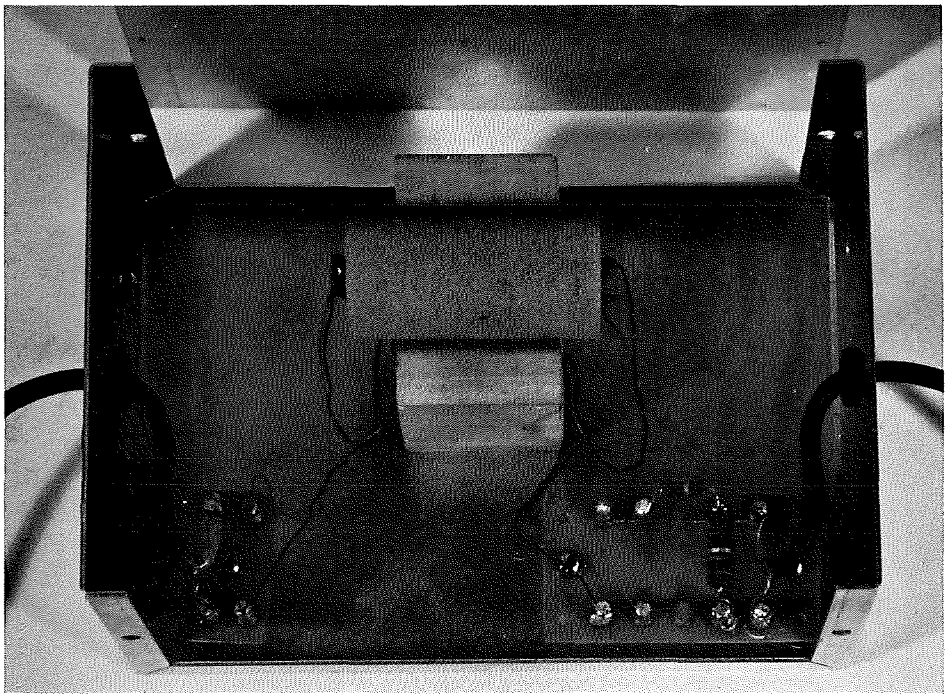


Figure E1 - Test Arrangement for Ultrasonic Studies Under Unstressed Conditions



(A) Test Specimen with Attached Crystals Located in Shield Box (Lid Removed)

(B) Associated Electronic Instrumentation

Figure E2 - Test Arrangement for Determining Ultrasonic Properties Under Unstressed Test Conditions

The first arrival signal is detected by the receiving crystal and is amplified and filtered, then routed to an oscilloscope where it is displayed and/or photographed. The filter primarily eliminates the low frequency components of environmental noise and provides a stable, clear signal for oscilloscope display. During testing the specimen was located in a shielded box wrapped in aluminum foil to reduce stray pickup. The crystals were attached to the finished end surface of the specimen by vacuum grease. This method presented no difficulties in the measurement of longitudinal velocity but was not particularly suitable for the measurement of absorption.

For absorption measurement, it was planned initially to compare the amplitudes of successive end-reflections. With the apparatus available, however, the method was not applicable since the end-reflected pulse was difficult to identify. Instead, the absorption was determined from the measurement of amplitude reduction of the first half cycle of the damped oscillatory wave form observed using specimens of different length. The coefficient of absorption B in db/in in the specimen was determined from the following formula:

$$B = \frac{1}{x} 20 \log \frac{A_x}{A_o}$$

where A_o is the amplitude of the received pulse at a distance x = 0 and A_x is the amplitude of damped pulse for a specimen of length x. The amplitude A_o was determined by direct contact of the transmitting and receiving crystals.

Initial studies were carried out on specimens of three homogeneous sedimentary rocks well known in the Rock Mechanics field. Tables E1 and E2 present the velocity and attenuation data obtained. In Table E1 the calculation of longitudinal velocity was based on the specimen length and the travel time. The maximum variation between results obtained from different runs on the same specimen was less than 4.9%. Attachment of the crystals to the test

TABLE E1

Longitudinal Velocity Data for Three Typical Sedimentary Rocks in the Unstressed State (After Kim [49])

Specimen Details				
Rock Type	Dimensions inches		Travel time** μ sec	Longitudinal velocity ft/sec
Indiana Limestone	length = 1.906	1*	12.5	12,700
	diameter = 1.75	2*	13.0	12,217
	length = 5.56	1	33.0	14,033
	diameter = 1.875	2	32.0	14,447
Crab Orchard (Tennessee) Sandstone	length = 2.094	1	19.0	9,183
	diameter = 1.125	2	18.5	9,425
Berea Sandstone	length = 2.25		26	7,200
	diameter = 1.063			

* Denotes first and second measurements on the same specimen.

** Crystals held in position using hand pressure only.

TABLE E2

Results of Study to Determine Velocity and Absorption in Berea Sandstone in the Unstressed State [Travel Time and Amplitude Data] (After Kim [49])

Specimen Number	Specimen Dimensions inches		Travel Time (μ sec) Mode of Crystal Attachment: Hand Pressure	Travel Time (μ sec) Mode of Crystal Attachment: Spring Loaded	Average Long. Velocity ft/sec	Amplitude (MV)+ Mode of Crystal Attachment: Hand Pressure	Amplitude (MV)+ Mode of Crystal Attachment: Spring Loaded	Average Absorption** (dB/in)
1	length = 2.056	1*	23	23		1.15	1.60	
		2*	23	23	7450	1.05	1.50	3.95
	diameter = 1.063	3*	23	23		0.90	1.60	
2	length = 2.032	1	22	22		1.25	1.30	
		2	22	22	7697	1.05	1.35	4.63
	diameter = 1.063	3	22	22		1.10	1.40	
3	length = 4.058	1	45	46		0.8	1.00	
		2	45	46	7352	0.8	0.95	3.17
	diameter = 1.063	3	45	46		1.0	0.90	
4	length = 4.125	1	46	46		0.5	0.95	
		2	46	47	7361	0.9	0.95	2.99
	diameter = 1.063	3	46	47		0.6	1.00	

* Denotes first, second and third measurement on same specimen.

** Average value of three measurements for spring loaded data.

+ Amplitude at distance x = 0 was 4 MV.

specimen using vacuum grease and handpressure appears to provide consistent velocity data. This was further demonstrated by the travel time data presented in Table E2, where tests were carried out in which crystals were hand loaded, and loaded using a spring arrangement. Very little difference in the resulting travel times were noted using these two methods of attachment, and those deviations noted represent an error in velocity calculation of less than 5%.

The data relating to measurement of attenuation to Berea Sandstone are presented in Table E2. Here the importance of the method of attachment of the crystal to the test specimen is clearly demonstrated. Differences between measured pulse amplitudes for crystals attached using hand pressure, and using spring loading differ by as much as 50%. The absorption values quoted were determined using the data from spring loaded tests. The absorption data obtained for the two different specimen lengths ($\ell \simeq 2''$ and $4''$) are somewhat different. The average values being 4.29 and 3.08 db/in. for the two and four inch long specimens respectively. This difference is assumed to be due namely to the losses at the contact between the driving crystal and the specimen. Variations between data obtained from two specimens of the same length were found to differ by less than 17%.

2.2 Preliminary Ultrasonic Tests on Greenwich Rock

Preliminary studies were carried out on rock specimens from the south Greenwich mine. Specimens of shale and sandstone obtained at a shaft sinking site (south air intake shaft, Area - C, see Figure 41) were studied. The data presented in Table E3 for these rocks were obtained under unstressed conditions.

TABLE E3

Longitudinal and Shear Wave Velocity Data Under Unstressed Conditions for Selected Specimens of Rock From the Greenwich Mine South Air Intake Shaft (After Kim [49])

Rock Type	Specimen No.	Direction to Bedding Plane	Longitudinal Velocity* ft/sec	Shear Velocity* ft/sec	V_s/V_1
Shale	1	Parallel	15,960	8,690	0.55
	2	Parallel	16,210	9,160	0.57
	3	Parallel	15,900	9,360	0.59
	4	Parallel	15,727	9,360	0.60
Shale	5	Perpendicular	13,375	-	-
	6	Perpendicular	13,240	8,040	0.61
	7	Perpendicular	12,244	9,240	0.76
	8	Perpendicular	12,250	7,300	0.60
	9	Perpendicular	13,050	7,750	0.59
Sandstone	10	Perpendicular	7,833	-	-
	11	Perpendicular	8,333	-	-
	12	Perpendicular	7,796	-	-
	13	Perpendicular	7,916	-	-

* Travel times used to compute velocity were determined using crystal transmitter - receiver pairs having resonant frequencies of 0.5, 1.0 and 1.5 MHz. No significant differences were observed. The velocity data presented is an average of the results obtained using the three different sets of crystals.

2.3 Detailed Ultrasonic Tests on Greenwich Rock

During the Fall of 1971 a number of the project staff met with the Greenwich Colliery geologist to obtain information in regard to the rock types and structure of the strata overlying the mine. During one of these meetings a number of diamond drill core samples, from holes drilled in the Greenwich area, were obtained for study in the laboratory. Table E4 gives the description and location of the various specimens prepared from these field samples. In all some twenty test specimens were prepared from sections of diamond drill core drilled mainly in an area located between the north and south mains and provided by the Greenwich geologist. The majority of these came from strata ranging from 250-400 feet below the surface. Since the coal seam in this mine is nominally under some 500 feet of overburden the material tested is representative of the strata more-or-less adjacent to the coal seam itself.

Atmospheric Tests: Table E5 presents the velocity and attenuation data for a number of the specimens measured under atmospheric conditions (i.e. no applied stress). In all cases the specimen velocity (longitudinal) was monitored perpendicular to bedding. In order to measure absorption a number of different lengths were measured for each specimen (e.g. for specimen No. 17 these lengths varied from 0.225-3.000 in.). In general the longitudinal velocities varied from 10,000 to 13,000 feet/sec; however, a few lower and higher values were noted. Values in the range 10,000 to 13,000 feet/sec are indicative of competant rock. Attenuation or absorption values varied in general from 4-8 db/in.

Uniaxial Tests: Measurements of the ultrasonic properties of a number of specimens of rock from the Greenwich mine were carried out under uniaxial compression to ascertain the effect of depth on these properties. Figure E3 illustrates the design of the loading arrangement utilized. A closed-loop

TABLE E4

Description and Location of Rock Specimens from Greenwich Mine
(After Kim [50])

Specimen Number	Diameter in.	Rock Type	Drill Hole Number	Depth from Surface ft.
4*	1.150	Shale variegated	C 6702	247
7	1.932	Shale gray sandy with lime-stone streaks	C 6702	264
8*	1.150	Shale and sandstone gray	C 6702	271
9	1.932	Fireclay-broken	C 6702	384
10	1.932	Shale gray with clay streaks	C 6702	390
11*	1.150	Shale gray sandy	C 6702	398
12*	1.150	Shale gray sandy	C 6702	407
17*	1.150	Shale gray with dark streak	C 6703	435
18*	1.150	Shale gray with dark streak	C 6703	435
32*	1.150	Fireclay	G 6910	336
36*	1.150	Shale gray sandy	G 6910	361
40*	1.150	Shale dark	G 6915	350
37	1.932	Fireclay sandy	G 6915	361
41	1.932	Shale dark sandy	G 6916	398
42	1.932	Shale dark gray	G 6916	409
44	1.932	Sandstone Shaley	G 6916	426
20	1.932	Shale dark gray	G 6701	396
22	1.932	Lime Shale	G 6701	420
27	1.932	Shale dark gray	G 6750	396
31	1.932	Shale dark	G 6750	432
9	1.932	Fireclay-broken	G 6702	384

* Recored from the original driller's core (diameter 1.932 in.).

TABLE E5

Longitudinal Wave Velocity and Absorption Data for Rock Specimens from the Greenwich Mine Under Atmospheric Conditions+ (After Kim [50])

Specimen Number	Dimensions - in. Diameter	Length	Travel Time msec	Velocity ft/sec	Amplitude* mv	Absorption - db/in A	B	C	D
17	1.15	3.000	19.8	12,626	190	5.9	4.2	3.3	
	1.15	2.490	17.0	12,206	230	6.5	5.7	---	
	1.15	2.190	14.7	12,415	280	6.6	---	---	
	1.15	0.225	1.6	11,718	1250	---	---	---	
18	1.15	2.958	21.3	11,573	210	4.6	3.3		
	1.15	2.448	17.6	11,591	255	4.9	---		
	1.15	0.432	3.2	11,250	800	---	---		
22	1.15	4.060	21.0	16,111	8	11.4	9.6		
	1.15	2.719	15.0	15,106	35	13.1	---		
	1.15	1.274	6.1	14,036	310	---	---		
27-1	1.93	3.944	26.5	12,403	15	4.3	4.9		
	1.93	2.718	17.2	13,168	30	3.9	---		
	1.93	1.167	8.0	12,156	60	---	---		
32-1	1.15	2.338	18.0	10,824	---	---	---		
40-1	1.15	2.345	15.5	12,608	---	---	---		
40-2	1.15	4.349	27.7	13,084	30	7.4	7.4	6.4	5.8
	1.15	3.586	22.4	13,340	50	7.8	7.8	6.7	---
	1.15	2.258	14.4	13,067	140	8.7	8.7	---	---
	1.15	0.682	4.4	12,917	680	8.1	---	---	---
	1.15	0.507	3.2	13,203	800	---	---	---	---
36	1.15	3.328	44.0	6,303	45	8.1	10.8	7.6	
	1.15	2.534	24.0	8,798	90	8.3	6.4	---	
	1.15	1.587	12.8	10,332	180	10.0	---	---	
	1.15	0.467	3.8	10,241	650	---	---	---	
12	1.15	3.231	21.8	12,351	240	4.0	3.1		
	1.15	2.703	18.1	12,447	290	4.1	---		
	1.15	0.460	3.2	11,979	850	---	---		

+ No applied stress.

* Signal amplitude observed at the receiving crystal.

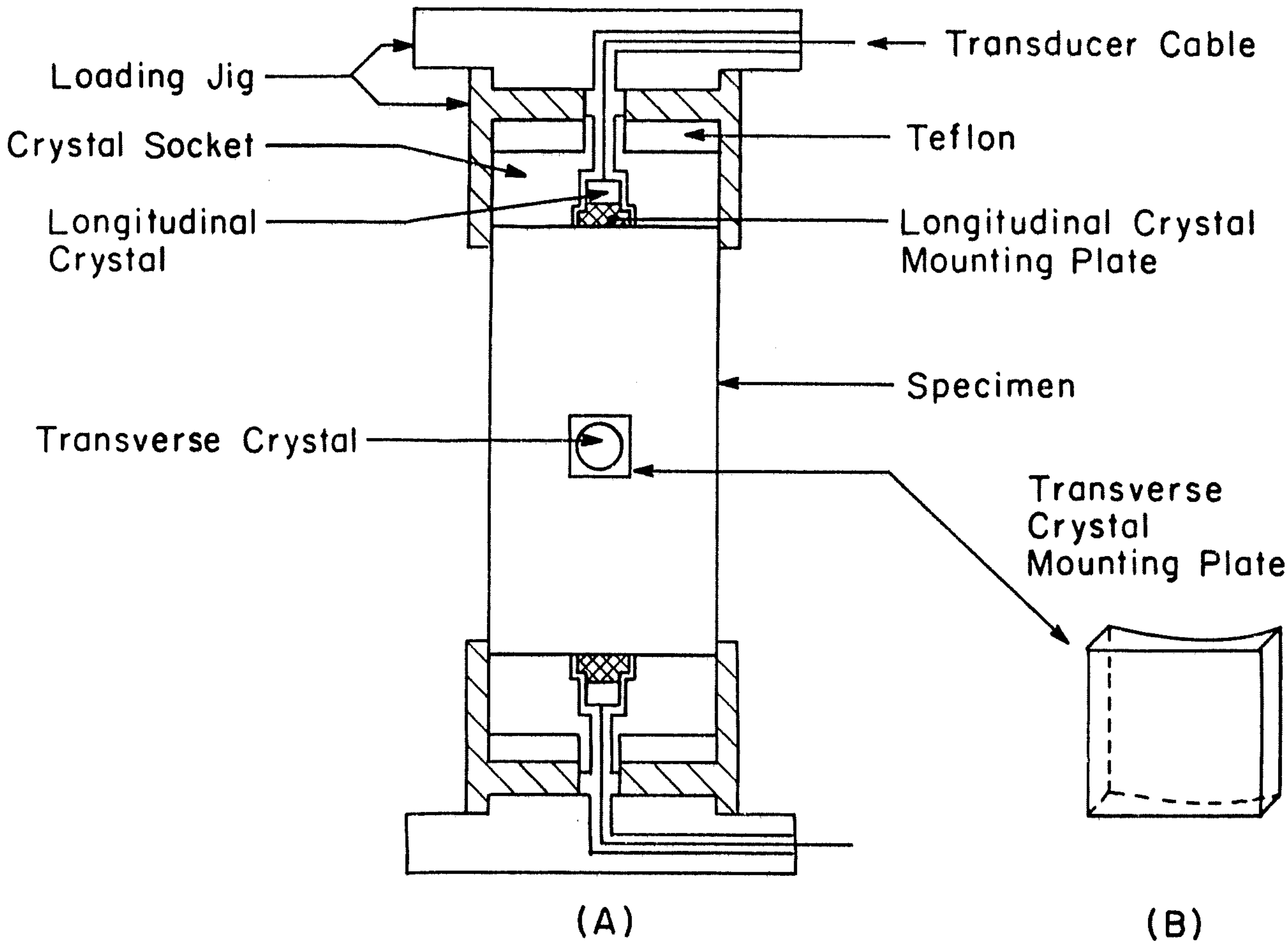


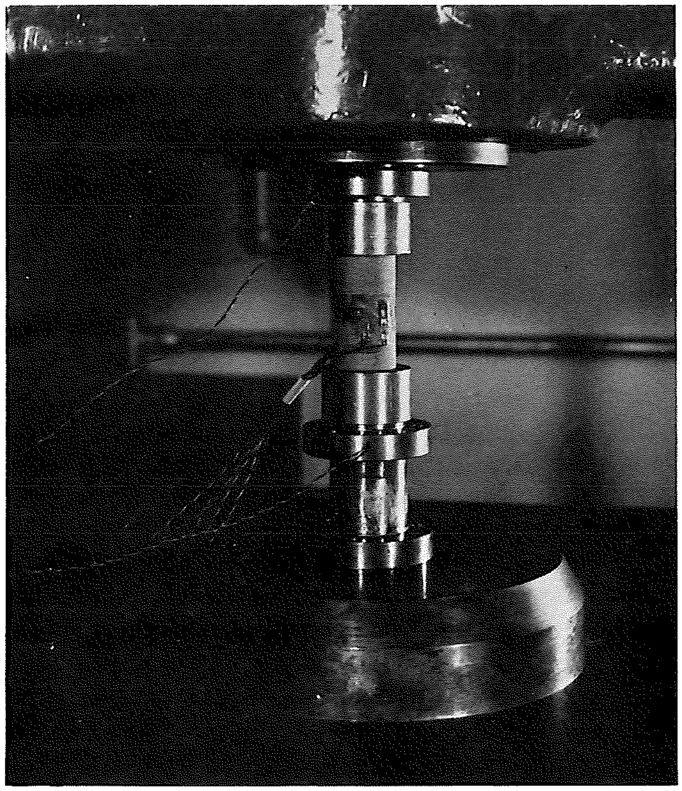
Figure E3 - Design of Loading Arrangement for Uniaxial Ultrasonic Studies
(After Kim [50])

electohydraulic testing machine was employed to apply the axial compressive load to the specimen. Ultrasonic measurements were made at a series of incremental axial compressive loads; the load being held for approximately 3 minutes at each increment. Figure E4 shows the overall measuring system undergoing tests prior to final tests in the closed-loop testing facility. Details of these studies are presented elsewhere (Kim [50]) however the data shown in Figures E5 and E6 are typical. In general the velocity measured parallel to the direction of applied load increased with stress level. The increases being of the order of 10-25% of the values obtained under atmospheric conditions. In contrast the velocity measured perpendicular to the applied load first increased then decreased above a certain stress level. Such behavior may be associated with the development of fractures parallel to the direction of loading.

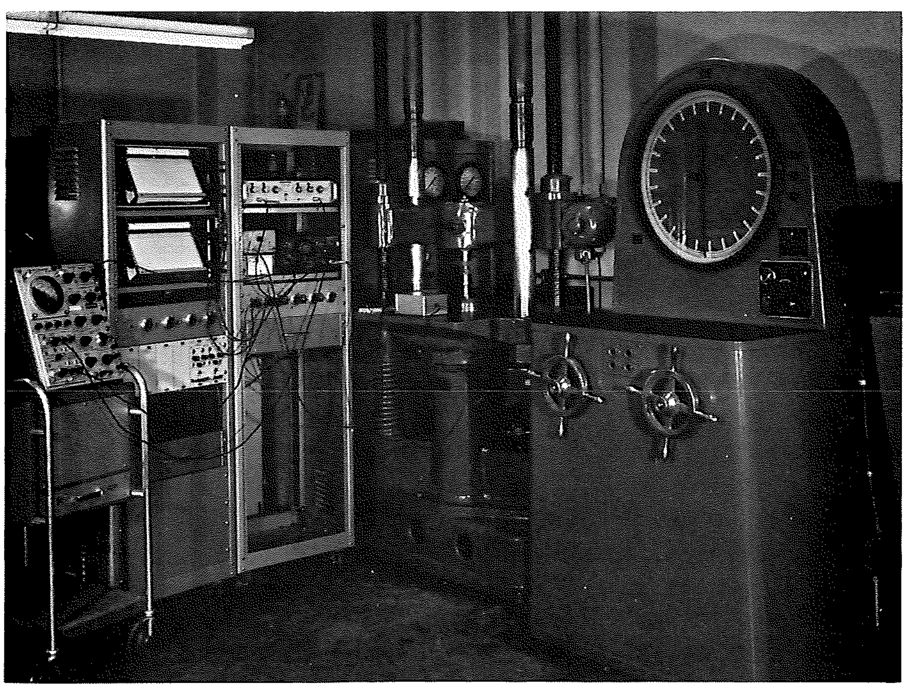
3. Strength and Elastic Properties

Strength and elastic properties were obtained for a limited number of rock specimens obtained from the Greenwich mine (see Table E4). Tests were carried out using standard facilities and techniques available in the Penn State Rock Mechanics Laboratory (see Hardy et al. [51]). In general specimens were loaded at 100 psi/sec up to failure during which longitudinal and transverse strains were monitored using attached foil-type strain gages.

Table E6 presents the compressive strength and elastic constants for a number of test specimens. From the data presented it appears that the overlying rocks were of considerable compressive strength (14,300-33,100 psi), however, it should be noted that in selecting sample material for specimen preparation obviously weak material is normally automatically rejected. Furthermore complete cores were not available making it impossible to estimate the general strength of the overlying rock.



(A) Test Specimen Mounted in Loading Arrangement



(B) Overall Loading and Monitoring System

Figure E4 - Test Arrangement for Determining Ultrasonic Properties Under Uniaxial Test Conditions

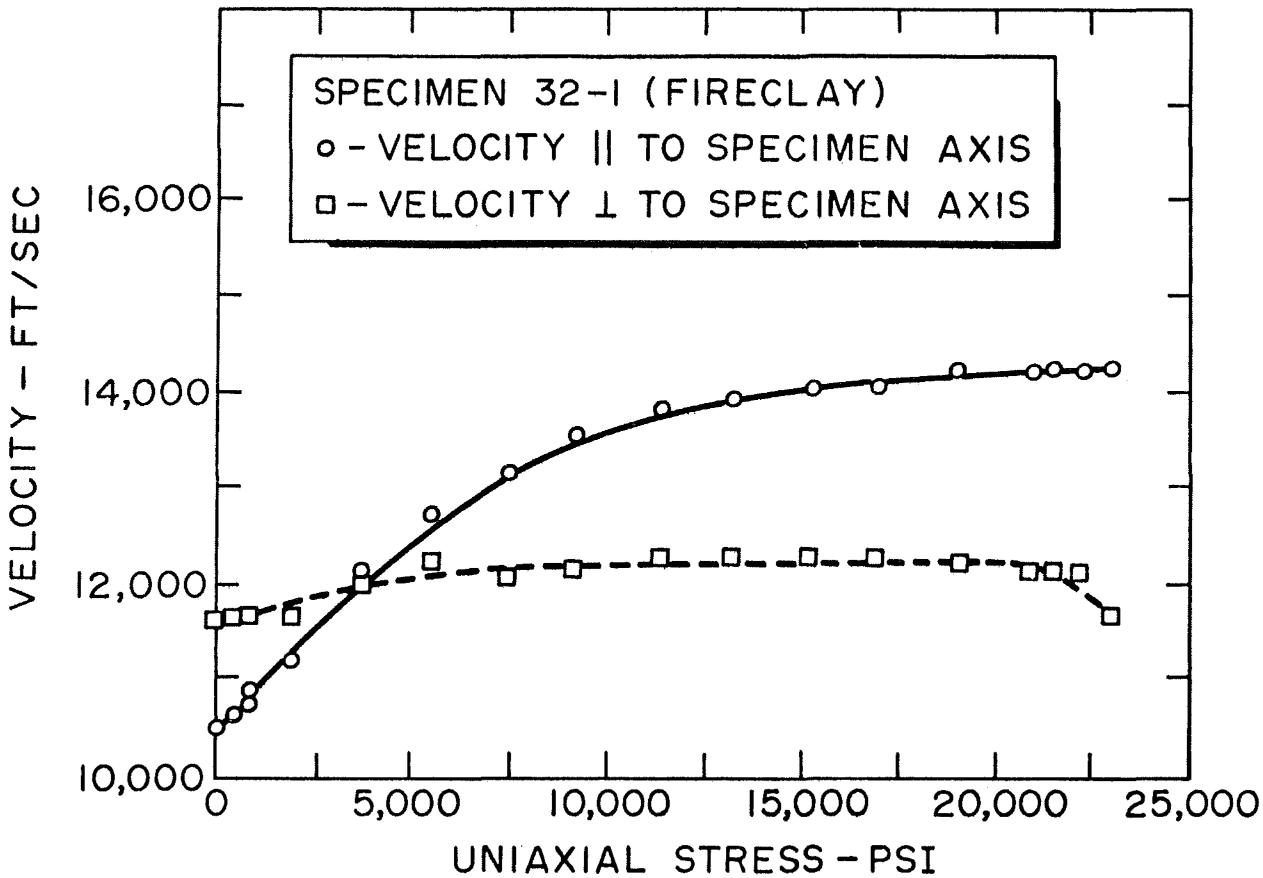


Figure E5 - Typical Variation of Longitudinal Velocity with Applied Axial Stress for Greenwich Fireclay (After Kim [50])

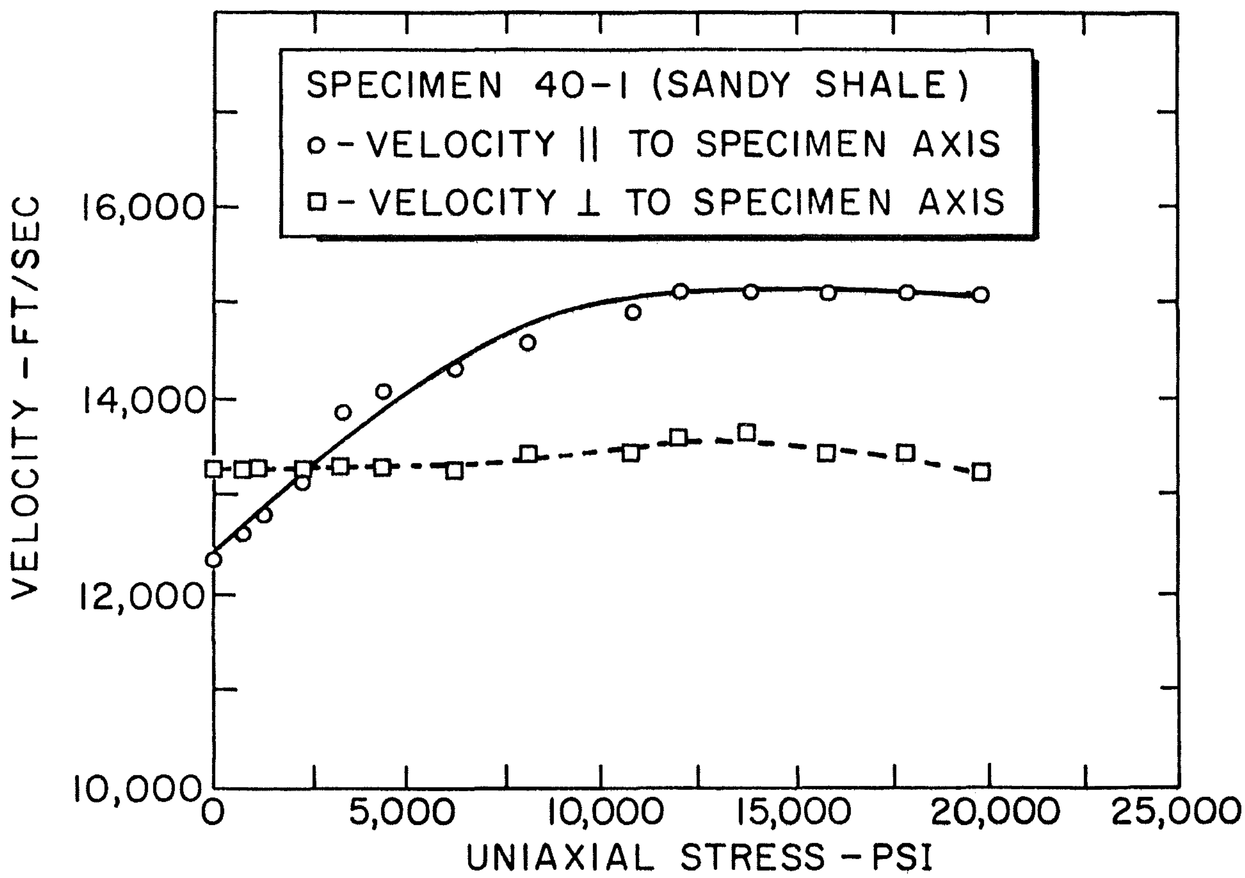


Figure E6 - Typical Variation of Longitudinal Velocity with Applied Axial Stress for Greenwich Sandy Shale (After Kim [50])

TABLE E6

Ultimate Strength and Elastic Constants of Rock
Specimens from Greenwich Mine
(After Kim [50])

Specimen Number	Rock Type	Specimen Dimensions Diameter in.	Length in.	Ultimate Strength psi	Young's Modulus 10^6 psi	Poisson's Ratio*
4+	Shale	1.150	2.192	20,100	---	---
11-1	Shale, Gray Sandy	1.150	2.275	33,100	8.10	0.13-0.28
11-2	Shale, Gray Sandy	1.150	2.264	17,900	4.13	0.08-0.16
32-1	Shale, Gray Sandy	1.150	2.337	23,000	4.60	0.01-0.16
40-1	Shale, Dark	1.150	2.345	19,800	4.03	0.03-0.16
9+	Fireclay, Broken	1.932	4.012	14,300	---	---
31+	Shale, Dark	1.932	4.058	18,600	---	---
37	Fireclay, Sandy	1.932	3.988	23,300	10.9	0.18-0.31

+ No strains were measured during tests on these specimens.

* Poisson's Ratio varied strongly with stress level.

The values of Young's modulus obtained (4.0×10^6 - 10.9×10^6) are indicative of fairly competant rock. In most cases the longitudinal stress-strain curves obtained were nearly linear, hence the Young's modulus values determined were for the most part independent of stress level. Poisson's ratio values on the other hand appeared to be highly stress dependent.

APPENDIX F

Specifications of Winkie Drill

1. Introduction

A portable diamond drill was purchased for the project in order to have the capability of drilling holes for deep geophone installations in locations inaccessible to heavy commercial drilling facilities. A Winkie model GW-15 drill* was selected after consideration of the various units available. A photograph of this unit is shown in Figure 26A earlier in this report.

This drill is a lightweight portable core drill. The drill was designed to recover 1" cores to a depth of 400'. In some formations, cores up to 2-1/8" in diameter can be recovered to lesser depths. A lighweight water pump is used to circulate water to remove the cuttings and to cool the bit. Diamond core bits specially designed or selected are used to cut the rock. In some softer overburdens, fishtail bits can be used to put the hole down to solid material. Table F1 lists the drilling capabilities of the unit. BX series tools were purchased for the current project.

TABLE F1

Model GW-15 Rated Drilling Capacities Using Mag-Zirk Light Weight Drill Rods

Core Barrel Series	Core Diameter		Hole Diameter		Depth+ Capacity	
	In.	M.M.	In.	M.M.	Feet	Meters
EX	7/8"	22	1-1/2"	38	400-450	120-138
EXT	15/16"	23	1-1/2"	38	400-450	120-138
AX	1-3/16"	30	1-7/8"	48	350-400	105-120
AXT	1-15/16"	33	1-7/8"	48	350-400	105-120
BX	1-5/8"	41	2-3/8"	60	150-200	45-60

\+ - Drilling capacities when using steel rods would be slightly less
Depth rating may vary due to particular rock formations and conditions.

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* Manufactured by J. K. Smit & Sons, Inc., Toronto, Canada.

2. Drill Design

The drill itself consists of three assemblies: (1) Engine, (2) Transmission and (3) Unipress.

2.1 Engine

The engine is a 10 HP, 2 cycle, air cooled gasoline engine. Easy starting with a nylon recoil type starter. A vacuum carburetor system allows drilling "up-holes" or at any angle. The engine is mounted with its drive shaft vertical so that it drives directly into the transmission.

2.2 Transmission Assembly

The transmission contains the clutch, gear box and water swivel. The engine shaft, through a splined connection, drives the centrifugal clutch. As the engine speed is increased past 900 RPM, the clutch shoes are thrown out and engage the clutch drum which rotates the input shaft to the gear box. If the engine speed should be reduced to lower than 900 RPM, the springs on the clutch shoe will pull the shoes in away from the inner drum surface and, power to the drill rods is removed.

2.3 Unipress

The Winkie Unipress enables the operator to exert a steady pressure with a minimum of exertion. Fatigue of the operator is reduced by 50% or more, contributing to more economical operation.

2.4 Water System

Circulating water through the drill rods down to the bit is required to wash out cuttings, cool the bit, and to keep the core from sticking. For this purpose, an engine-pump unit complete with hoses and water by-pass system is available. The pump is a Robbins & Myers Model FS-22 progressing cavity water pump mounted integral with a 3 HP gasoline engine. Pump rating is 8 GPM at 150 psi. Since the pump runs constantly with the engine, a pressure valve relieves pressure on the pump, if for any reason, the bit or rods become clogged.

A 3/4" x 17', 4-ply, pressure hose with fittings and shut-off valve, and a 3/4" x 12', 3-ply, suction hose with fittings, foot valve and strainer are part of the water system unit. A suitable water supply is necessary. For field work, it may be necessary to use a water tank or drum for the water. If the formation is solid enough, it may be convenient to recirculate the water from the hole to the tank. In this case, a "T" joint on top of the casing is required to direct the water to the tank.

3. Operation

During the Summer of 1973 initial drilling operations were carried out using the Winkie unit at the Greenwich Mine site. A considerable number of difficulties were experienced in drilling the first few holes but as the field crew became more familiar with the unit the difficulties decreased. A brief report* prepared by one of the project personnel, involved in this initial drilling program, is included here for the benefit of future users.

3.1 Set-up

The Winkie is light weight and relatively low powered (which has advantages and disadvantages). A set-up using an "H" frame for drill mounting was found quite satisfactory. However, splaying the side members of the "H" to approach an "A" shape with the wide end towards the rear should be better. It may also be advantageous to have the steadying spikes set at an angle say 60° or so (with horizontal). The importance of a steady set-up cannot be overemphasized.

3.2 Start-up

(1) Always check that the gear lever is in neutral before starting.

(2) Close choke, open throttle about 1/8 and crank briskly 2 or 3 times to prime.

(3) Open choke, open throttle 1/4 to 1/3 and crank briskly 2 or 3 times or until it starts.

(4) If after a few cranks it does not start repeat step 2. (The engine may start-up at step 2, if so be prepared to close choke and open throttle to maintain a good warm-up speed.)

(5) Always warm up engine before starting work. Slowly increasing the speed up to about 1/2 or 1/3 throttle with faster return to idle speed is best.

(6) Before shifting gears return engine to idle speed.

Personal Communication with W. Comeau, presently with Hydro-Quebec, Montreal, ada.

(7) Water pump should be started up by now also. Don't try to start with by-pass closed (it is very difficult). See Figure F1 for details of drilling fluid system. Check pump intake periodically for blockage.

3.3 Drilling Overburden

Basic overburden drilling tools (in order of preference) are as follows:

BX coring

a. Roller cone bit (2-3/8" diameter one employed during initial field use).
b. Drag bit
c. Diamond core bit

B casing

a. Drive shoe
b. Sawtooth
c. Diamond bit

In clean overburden (no stones) the auger is a very fast drilling tool.

To start hole in overburden (up to 20' deep):

(1) Drill with roller cone bit to rock (use minimum water, return fluid should be thick and soupy). Use low gear and high engine speed.

(2) Set drive shoe on casing and drive with hammer (carefully guide first 6' length).

(3) Keep driving till advance stops. If casing is set in rock (easily checked by comparing depth of casing with depth attained by roller bit), clean out with drag bit or roller if available to fit inside casing. Flush with generous water supply and when return is clear start coring. Casing must be well set in rock before this step is attempted.

(4) If casing is not set in rock, clean out inside of casing and re-drive until it is.

(5) In cases where it is impossible to set casing tightly in rock with drive shoe, remove it and use a diamond shoe and drill casing in rock. Before attempting this it is best to core a foot or so before removing casing. Where overburden caves easily, leave drill rods with starting core barrel in hole as this will guide casing when re-entering with diamond bit on casing.

(6) Casing can be advanced in rock using the "leap frog" method, i.e. drilling ahead with core barrel and following with casing.

(7) Alternative methods of advancing casing are:

a. Running in with sawtooth bit gives best results in clayey ground (with or without predrilled pilot hole).

b. Running in with diamond bit (with or without predrilled pilot hole).

<u>CAUTION 1</u> - Using the sawtooth bit in stony ground, and when trying to set the casing in fractured bedrock, will result in excessive vibration and eventual destruction of the bit by chipping of the carbide teeth.

<u>CAUTION 2</u> - Use of the diamond bit on the casing may be necessary in stony ground where the drive shoe cannot penetrate. However, overburden is generally highly abrasive and can rapidly destroy the bit.

3.4 Drilling Rock

Rock drilling is not quite as complicated as overburden drilling. However, it is generally more expensive so greater care is required.

<u>Do</u>: Always use started barrel with a good but <u>used</u> bit to collar-in on bedrock.

<u>Do</u>: Always start rotation about one inch off bottom with water turned on advancing slowly till bit contacts rock.

<u>Do</u>: Always be sure there is water return before commencing drilling (unless hole is very short and in badly broken rock and it is reasonably sure that water is getting to bit).

<u>Do</u>: Always concentrate on the drilling process, being ready to act fast should something start to go wrong.

<u>Do</u>: Always keep the threaded parts of tools clean.

<u>Never</u>: Drop rods with a diamond bit on the end into the hole.

<u>Never</u>: Drop any metallic particles in the hole.

<u>Never</u>: Start drilling without being sure water is flowing past bit.

<u>Never</u>: Use pipe wrench jaws on the diamonds (grip where there are none!).

<u>Never</u>: Try to bull through with brute force. It is the intelligent application of force that produces results.

The main thing to remember is do not lose rotation. If the operator is paying attention to the drilling process he will feel when things start to tighten up and he can slack off early, or when the drilling process slows remarkably (this means a blocked bit, core jammed in barrel or barrel full, or if applicable a very hard band of rock) and it is time to pull out and empty core barrel or see what is wrong.

CAUTION 3 - Should water stop returning while drilling a run, be prepared to stop at the slightest sign mentioned above. Better be safe than sorry. With BX tools or larger the Winkie does not have enough power to really jam itself or completely destroy the diamond tool. However, when using smaller diameter tools, special care must be taken to prevent damage.

4. Coring Tools

There are two types of coring bits:

1. Carbide tooth
2. Diamond

Unless the rock is very soft only the diamond bit can be used. This is especially true for the Winkie because of the very limited amount of down force available. It should be noted that no rock, soft enough to core with a carbide bit, was encountered during initial field trials.

When reordering diamond coring bits for field use it is recommended that the following be specified:

(1) Small highest quality diamonds (one or two grades smaller than normally recommended).

(2) "Sharp set" if this service is available.

(3) Reduced number of stones compared with normal recommendation (1/3 to 1/2 reduced).

(4) At least four or more shallow waterways (since reduced number of stones in groups, leave a shallow waterway between the groups. As there are less diamonds there will be more space for shallow waterways). Note that it is important that the waterways be shallow.

Although they were not included in the original system, the two pressure gages shown in the figure are not only desirable but necessary for serious drilling. Actually, had they been available, problem situations encountered would have been reduced or eliminated. For example, drilling in solid rock with no water because operator thought he was in overburden, and loosing water in fissures while coring with the diamond bit. With the system shown the following optimum procedure may be followed:

(1) The pump can best be started with the by-pass valve open and the main valve closed.

(2) The by-pass valve can be closed after the pump motor is operating satisfactorily and the pump pressure gage and drilling gage checked to ascertain that the pump is supplying maximum pressure (150 psi).

(3) The relief valve should be blowing off excessive pressure at this stage.

(4) Just before drilling is to commence, open the by-pass valve about 2-1/2 turns. This will result in a drop in pressure as water is recirculated from the reservoir through the pump and back to the reservoir.

(5) When drilling is to commence (before actually applying down pressure and in the case of a diamond bit before it touches the rock), open the main valve so as to obtain a visible return. Only when this return is seen should actual drilling commence.

(6) In order to correctly interpret the fluctuations of the pressure gages during the drilling operation, it is worthwhile to simulate blocked drilling rods by closing off the main valve and observing the gages.

(7) Once experience with the reaction of the water pressure gages to various drilling situations has been acquired, one will automatically know by constant observation of the gages what to do.

(8) Whenever the gages indicate a block in the flow to the bit, pull out and evaluate the problem.

(9) It is conceivable that under certain conditions the by-pass valve will have to be closed to route the entire pump output through the drill rods. However, as mentioned in the Winkie manual, a minimum of fluid to assure efficient drilling is desirable.

<u>CAUTION 4</u> - Good drilling practice involves constant observation of the drilling fluid gage.

APPENDIX G

Miscellaneous Equipment and Components

I. Manual Analysis System

1. Honeywell Model 5600C Tape Recorder
2. Honeywell-SAICOR Model SAI-52B Real Time Spectrum Analyzer-Digital Integrator
3. Model 82 Biomation Transient Recorder
4. Hewlett-Packard Model 7004A x-y Plotter
5. Hewlett-Packard Model 5326A Timer-counter
6. Hewlett-Packard Model 5055A Digital Printer
7. Magnetic Recording Tape for Honeywell Tape Recorder

   7.1 10-1/2" reels, 3600 foot roll, 1 mil Polyester base magnetic instrumentation tape

   7.2 3M Company Part No. 871-1-3600IR

II. Seismic System

1. Bison Model 1570B Signal Enhancement Seismograph System
2. Bison Model 1430 Blaster Unit

III. Laboratory Velocity Measurement System

1. General Radio Type 869-A Pulse Generator
2. Krohn-Hite Model 310-C Bandpass Filter
3. Tektronic Type 502 Dual Beam Oscilloscope
4. Transmitting and Receiving Crystals [PZT-4, resonant frequency 200 kHz, manufactured by Erie Tech, State College, Penna.]

APPENDIX H

Field Velocity Measurements

1. General

In order to locate the source of individual microseismic events it is necessary to have accurate values of the velocity for the materials through which the associated stress waves propagate. When the microseismic transducer array is located underground the necessary data for compution of the velocity may often be obtained by monitoring underground blasts associated with routine mining operations. However when a surface array, such as utilized in this project, is involved the problem of obtaining the necessary velocity data becomes more difficult. Under these conditions the velocities required are those associated with the complex strata overlying the mine. Studies to investigate the most suitable means for determining these velocities have been under way since the Spring of 1973. Details of these studies will only be briefly outlined here since this work is the topic of a thesis by one of the project personnel (Beck) to be completed later this year.

Basically three different methods for evaluating overburden velocities have been studied, namely:

1. Surface refraction techniques,
2. Down-hole, techniques, and
3. Direct techniques.

Surface refraction studies have been made using a two-dimensional array located over the West B-4 longwall area. At the air return site down-hole studies have been carried out at the borehole probe site, and direct studies at a rock dust hole site. It should be noted that these studies are continuing and results presented in subsequent sections are tentative.

2. Surface Refraction Studies

Shallow refraction studies have been made using a commercial, single transducer, seismograph (Bisom Model 1570B) with hammer impact for the seismic source. Deep refraction studies have utilized explosive charges for the seismic source and both the seismograph and the microseismic monitoring facility (with 6 or 7 transducer linear array). Figure H1 shows a photograph of the Bison seismograph and associated blaster used in these studies.

Shallow refraction studies using hammer impact as the seismic source indicate a soil velocity of 1000-2000 feet/sec and a rock velocity of 7500-8500 feet/sec. Deep refraction studies using explosives for the seismic source indicate rock velocities of the order of 7000-12,000 feet/sec.

3. Down-Hole Studies

In these studies surface explosive charges were utilized as seismic sources and the borehole probe (located at different depths in a 130' deep bore hole) was utilized for detection. In all some 15 tests were carried out and resulting velocities varied from 3500-11,000 feet/sec depending on probe depth.

4. Direct Studies

The direct studies involved attachment of the monitoring transducers to a metal plate bonded to the roof of the mine. Access was accomplished via a set of holes used for transport of rock dust into the mine. Explosive charges located on surface directly above the mine (approximately 430') were used as seismic sources. Results for four tests ranged from 9,619-9,794 feet/sec for the overall velocity (rock + soil). The value for the rock itself will be somewhat higher when correction is made for the contribution of the low soil velocity.

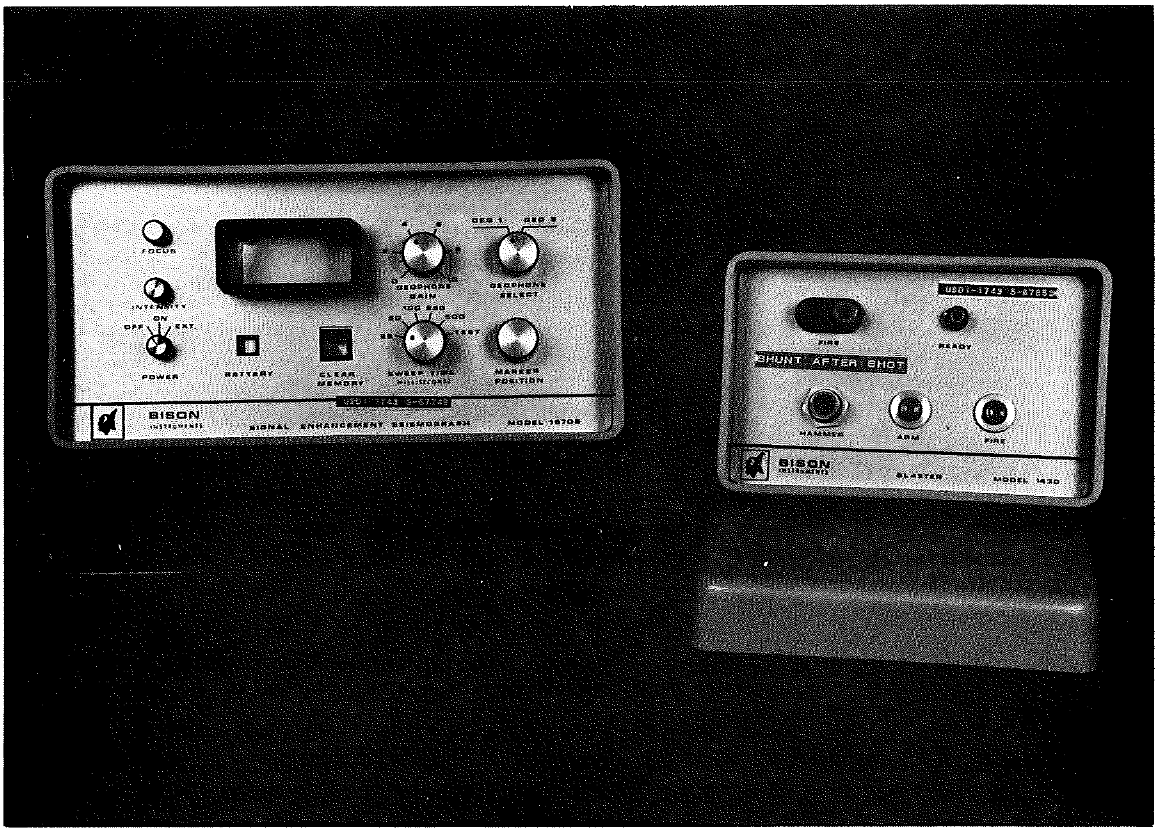

Figure H1 - Bison Seismograph and Blaster Unit

APPENDIX I

Survey Data for Transducer Locations at Air Return and West B-4 Longwall Sites, Greenwich North Mine

This appendix contains the 3-dimensional coordinates of transducer locations for the air return and West B-4 longwall sites at the Greenwich north mine. The associated surveys were carried out by project personnel using instrument station coordinates provided by the Greenwich mine survey group.

TABLE I1

3-Dimensional Coordinates of Transducer Locations at Greenwich Air Return Site

Instrument Station: 1030

Known Coordinates of Instrument Station: [1697988.27, 503918.21, 1581.76]

Known Bearing of Course 1030 to 1031: N 45° 45' E

Survey Date: March 26/27, 1973

Point	Length	Diff. in Elevation	Reduced Bearing	EASTING (X)	NORTHING (Y)	ELEVATION (Z)
1031	265.65	+ 9.58	N 45° 45' E	1698177.80	504102.84	1588.71
L-5*	459.66	+ 24.90	N 62° 05' E	1698177.80	504133.42	1606.55
L-4	408.92	+ 28.94	S 84° 12' E	1698395.10	503876.89	1610.70
L-7	691.27	+ 82.01	S 66° 49' E	1698623.76	503646.17	1663.77
L-1	411.97	+ 40.89	S 44° 10' E	1698275.31	503622.70	1622.65
L-6	79.72	- 10.01	S 9° 40' W	1697974.88	503839.62	1571.75

* L-5 etc. denote transducer locations shown on Figure 44.

TABLE I2

3-Dimensional Coordinates of Transducer Locations at Greenwich Air Return Site

Instrument Station: 1165

Known Coordinates of Instrument Station: [1698461.51, 503128.36, 1629.80]

Known Bearing of Course 1165 to 831: N 4° 14' W

Survey Date: March 26/27, 1973

Point	Length	Diff. in Elevation	Reduced Bearing	EASTING (X)	NORTHING (Y)	ELEVATION (Z)
831	161.00	+ 1.03	N 4° 14' W	1698449.61	503289.07	1630.83
L-9*	255.97	+ 2.26	S 27° 14' W	1698344.37	502900.66	1632.06
L-3	110.98	+ 1.03	S 75° 43' W	1698353.96	503100.88	1630.83
L-2	126.00	+ 0.19	N 24° 51' W	1698301.01	503215.21	1629.99

* L-9 etc. denote transducer locations shown on Figure 44.

TABLE I3

3-Dimensional Coordinates of Survey Instrument Stations at Greenwich West B-4 Longwall Sites

Instrument Station: Base Point
Known Coordinates of Instrument Station: [4699399.68, 503937.09, 1665.69]
Known Bearing of Course Base Point -1054: N 30° 53' W
Survey Date: March 26/27, 1973

Point	Length	Diff. in Elevation	Reduced Bearing	EASTING (X)	NORTHING (Y)	ELEVATION (Z)
1054	70.95	- 1.69	N 30° 53' W	4699363.26	503997.98	1664.00
1	41.00	0.00	S 75° 31' W	4699323.56	503926.84	1665.69
2	101.00	0.00	N 75° 31' E	4699497.47	503962.35	1655.69
3	220.54	+ 9.94	N 75° 31' E	4699613.21	503992.25	1675.63
4	310.56	+ 11.75	N 75° 31' E	4699700.37	504014.76	1677.44
5	460.58	+ 13.92	N 75° 31' E	4699845.62	504052.28	1679.61

Instrument Station: 5
Known Coordinates of Instrument Station: [4699845.62, 504052.28, 1679.61]
Known Bearing of Course 5 to 4: S 75° 31' W
Survey Date: March 26/27, 1973

Point	Length	Diff. in Elevation	Reduced Bearing	EASTING (X)	NORTHING (Y)	ELEVATION (Z)
4 (Back sight)	150.02	- 2.17	S 75° 31' W	4699700.37	504014.76	1677.44
6	100.94	+ 2.47	N 75° 31' E	4699943.35	504077.52	1682.08
7	170.89	+ 4.17	N 75° 31' E	4700011.08	504095.02	1683.78

TABLE I4

3-Dimensional Coordinates of Transducer Locations at Greenwich West B-4 Longwall Sites

Instrument Station: 1053

Known Coordinates of Instrument Station: [4699268.36, 504156.66, 1664.00]

Known Bearing of Course 1053 to 1054: S 30° 53' E

Survey Date: April 9, 1973

Point	Length	Diff. in Elevation	Reduced Bearing	EASTING (X)	NORTHING (Y)	ELEVATION (Z)
1054	184.89	0.00	S 30° 53' E	4699363.26	503997.98	1664.00
G-1*	185.94	+ 3.25	N 88° 28' W	4699082.49	504161.64	1667.25

* G-1 denotes transducer location shown on Figure 62.

TABLE 15

3-Dimensional Coordinates of Transducer Locations at Greenwich West B-4 Longwall Sites

Instrument Station: 1054

Known Coordinates of Instrument Station: [4966363.26, 503997.98, 1664.0]

Known Bearing of Course 1054 to Base Point: S 30° 53' E

Survey Date: April 9, 1973

Point	Length	Diff. in Elevation	Reduced Bearing	EASTING (X)	NORTHING (Y)	ELEVATION (Z)
Base Point	-----	-----	S 30° 53' E			
G-7*	111.00	+ 0.65	N 29° 11' E	4699417.38	504094.89	1664.65
G-5	206.00	0.00	N 32° 08' W	4699253.69	504172.42	1664.00
G-4	170.95	+ 2.99	N 78° 35' W	4699195.69	504031.82	1666.99
G-2	240.95	+ 3.50	S 82° 43' W	4699124.25	503967.43	1667.50
G-3	160.97	+ 2.34	S 59° 11' W	4699225.01	503915.54	1666.34
G-6+	-----	-----	-------	4699225.01	503910.54	1666.34

* G-7 etc. denote transducer locations shown on Figure 62.

+ G-6 located five feet south of base point.

TABLE I6

3-Dimensional Coordinates of Transducer Locations at Greenwich West B-4 Longwall Sites

Instrument Station: 3

Known Coordinates of Instrument Station: [4699613.21, 503992.25, 1675.63]

Known Bearing of Course 3: Base Point - S 57° 00' W

Survey Date: April 13, 1973

Point	Length	Diff. in Elevation	Reduced Bearing	EASTING (X)	NORTHING (Y)	ELEVATION (Z)
B.P.	-----	-----	S 75° 00' W	-----	-----	-----
G-10*	116.00	- 0.18	N 19° 27' E	4699651.04	504101.63	1675.45
G-13	240.04	+ 3.98	N 75° 31' E	4699845.62	504052.28	1679.61
G-12	230.26	+ 13.08	S 69° 06' E	4699828.32	503910.11	1688.71
G-11	180.42	+ 10.21	S 26° 54' E	4699694.84	503831.55	1685.84
G-8	165.87	+ 10.31	S 31° 01' W	4699527.74	503850.10	1685.94
G-9+	-----	-----	-------	4699613.21	503992.25	1675.63

* G-10 etc. denote transducer locations shown on Figure 62.

+ G-9 located at survey point 3.

APPENDIX J

Log of Diamond Drill Core from Microseismic Probe Borehole at Air Return Site, Greenwich North Mine

Footage	Rock Type	Comments
0-11.5'	soil	augered - no core recovery, no samples of soil taken
11.5'-15.5'	sandstone	grey-white, coarse-fine with small black silt lenses, at bottom black sandy siltstone
15.5'-19.0'	shale or clayey siltstone	soft easily crumbled, grey-white in color, highly fractured, no sand size particles noted, no acid reaction
19.0'-19.75'	shale	black silty, highly weathered, breaks into chips
19.75'-21.0'	shale or clayey siltstone	same comments as 15.1'-19.0' interval
21.0'-21.8'	sandstone	hard white-grey with iron stain at bottom
21.8'-30.0'	siltstone or shale	grey-brown, highly weathered, highly fractured, easily crumbled; grey color increases with depth, appears to grade into grey shale beneath; at 28' a few lenses of sandstone
30.0'-34.0'	shale	grey, highly fractured perpendicular to the hole, easily crumbled, laminae present
34.0'-40.7'	shale	dark grey, crumbles perpendicular to hole, laminae present
40.7'-41.0'	coal/siltstone	mixture of bituminous coal and dark grey siltstone
41.0'-42.0'	shale	dark grey, indurated grading into material below
42.0'-43.0'	shale	soft grey grading into material below
43.0'-44.6'	shale	light grey, crumbling, highly eroded and fractured apparently from drilling; slight acid reaction
44.6'-48.6'	shale	grey to light grey, calcareous silty; less acid reaction at bottom of section