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EXCAVATION AND SEISMOLOGY

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20. ABSTRACT (continued)

the program emphasized the development of a seismic source/receiver combination which produces a simple, repeatable transmitted seismic pulse. A field recording system was assembled and seismic signals recorded and digitized for reflections from free surfaces on granite blocks and in situ using a single receiver at various locations to simulate an array of receivers. The digitized signals were subsequently processed by digital computer to simulate and assess signal processing techniques.

In the final part of the program the field recording system was used to collect fault reflection data in an underground copper mine. By computer processing, a movie display was produced showing the reflected seismic wave from the fault. The final report discusses experimental procedures and interpretation and the problems encountered in the underground environment.

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Final Technical Report

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TECHNICAL REPORT SUMMARY

The purpose of this study was to investigate the applicability of seismic sensor array techniques for fault and hazard detection in underground excavations.

In the first phase, a number of fixed and adaptive array-processing techniques were evaluated for performance and simplicity of implementation. Using crossed-line arrays of six to nine elements in each line, the feasibility of detecting and identifying reflections from free surfaces was demonstrated using data recorded on large granite blocks. A combination of adaptive null filtering on each of the two line arrays followed by cross-correlation of the resulting filtered signals was found effective in substantially reducing surface wave interference which obscured the reflected pulse. However, attempts to utilize this technique to detect known faults in granite with surface-emplaced arrays were inconclusive.

In the second and final phase of the study, the experimental techniques of the first phase were modified for underground use. In most hard-rock excavations, surface emplacement of the seismic source transmitter and receiver arrays would not be possible. Consequently, the receiver sensor was modified for emplacement in a small diameter borehole drilled into the wall or floor of the opening. The pulsed piezoelectric source was replaced with a spark discharge source which could similarly be used along a small diameter borehole.

Also, a new type of operator display was used in the second phase. This display provides a three-dimensional image of a reflected wave arriving simultaneously at all array elements. As such, reflections can be detected more readily by an untrained operator. A total of 15 receiver sensor positions and 15 source transmitter positions, giving an effective array size of 225 elements, was found to be adequate for this display concept.

Testing was done underground at the White Pine Copper Mine at White Pine, Michigan. This phase was concerned with using the methods which were previously developed to detect faults. A known fault was successfully detected at a distance of four feet but was not successful at a range of eight feet and greater.

The technique of emplacing the sensor and source arrays in boreholes was effective in eliminating interference from surface waves which were a problem when surface emplacement was used. However, with borehole emplacement, reflections from the rock surface are present and have to be identified and disregarded.

The recorded pulse waveforms are marginal at best, and had to be heavily filtered to obtain useful results. Observed ringing effects and low frequency oscillations were probably associated with the method of accelerometer mounting and the electronic recording equipment, although this conclusion could not be directly verified.

An interesting and possibly useful phenomenon observed during the underground testing was a period of microseismic activity in the 5 kHz-20 kHz range which was detected by our receiver accelerometers. This activity correlated with a significant increase in rock falls, cracking, and pillar robbing within the mine.

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SECTION I

INTRODUCTION AND SUMMARY

This report describes the experimental and analytical results of the final phase of the Excavation Seismology contract. This phase was concerned with using the equipment and methods, previously developed, to collect data from rock faults in an underground mine. The procedure successfully detected a known fault at 4 foot range but was not successful at 8 foot and greater ranges.

Goals of This Study

The primary goal of this work was to test the feasibility of using acoustic imaging to detect faults in rock. A similar method has been successfully used in seismic exploration (ref. 1). In that application the acoustic energy was produced by explosive charges; the image area was 2 miles x 2 miles and the penetration depth was thousands of feet. The present study was concerned with using similar means to detect faults in front of an advancing tunnel face, using procedures that can be adapted to commercial mining.

Outline of the Method

An acoustic pulse induced in the rock will propagate on a spherical wave front. This wave will be partially reflected at a fault, and the reflected wave can be detected by a plane array of acoustic sensing elements (see Figure 1).

As the reflected wave passes through the sensor plane, the intersection of the expanding wave front and the plane will be an expanding circle. The sensing element outputs at successive instants will show the positions of the expanding circle. A movie of the expanding circle can be made by constructing a set of pictures of the sensing array and showing the instantaneous sensor outputs on the pictures. Information about the reflecting surface can be gotten by measuring the images on the successive movie frames.

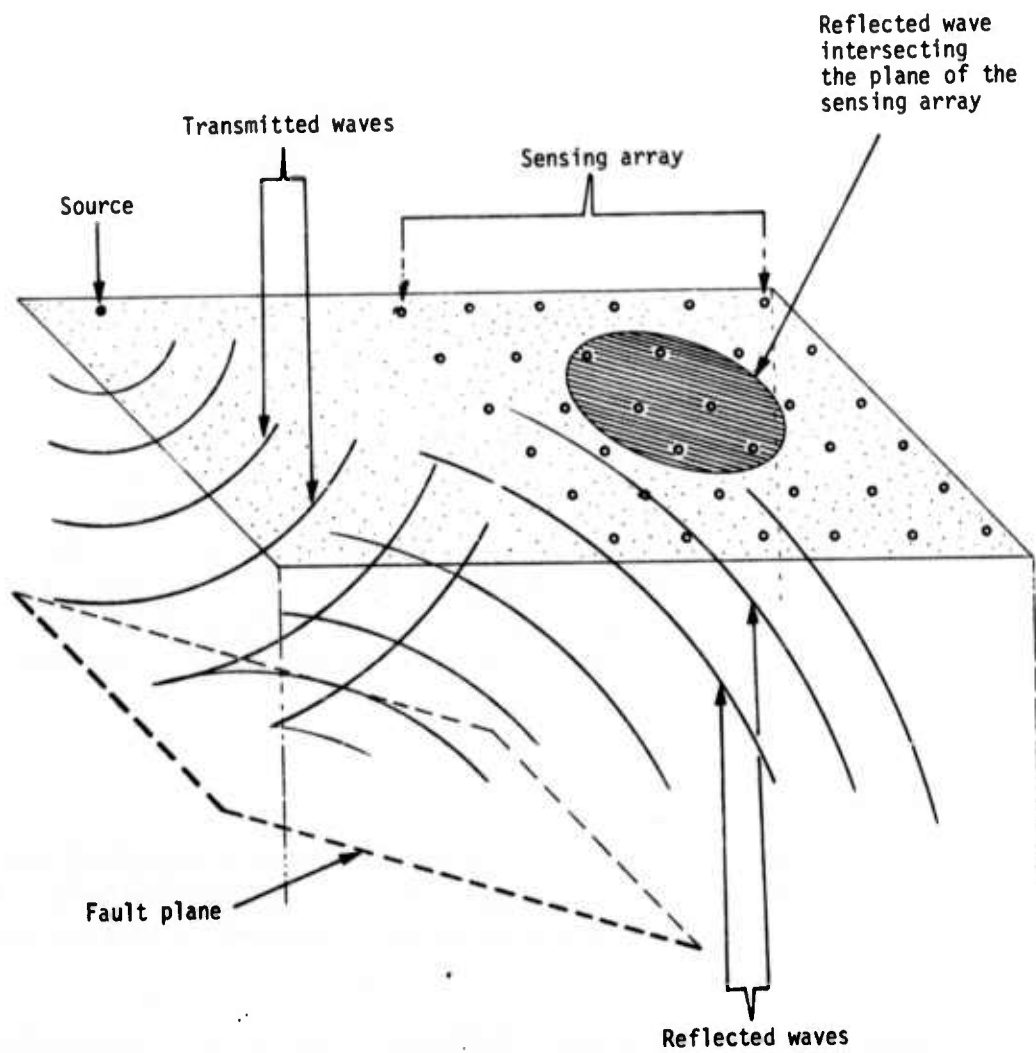


Figure 1. Detection of Fault by Sensing Array.

A similar movie can be made using other source and sensor arrangements. One alternative replaces the single source with a line of source positions and replaces the 2-dimensional sensing array with a line of sensing elements. The two lines are positioned so they intersect and part of the resulting plane becomes the equivalent sensing array (ref. 2). This was the arrangement used in this study.

The sensor outputs must be recorded in order to make the movie. With a single source and an $N \times N$ sensing array, N^2 data channels must be recorded, each corresponding to a different position in the sensing array. For the two-line method, there are N different source positions and N different sensor positions. Thus there are still N^2 data channels to record, each corresponding to a source-sensor position pair and to a position in the equivalent plane sensing array.

In surface based seismic exploration, it is easy to deploy a 2-dimensional sensing array. However, in an underground mine, there are few available plane surfaces, and it is hard to deploy a 2-dimensional array within the rock. The two-line method can be implemented underground by drilling two holes in the rock. This is a major reason for using the two-line method.

Underground Data Collection

The underground data collection was done in the White Pine Copper mine at White Pine, Michigan. The older part of this mine contains an area that has been frequently used for mining experiments. This area, while being neither a laboratory nor an active mining area, provided necessary features of both environments. Power, water, storage area, etc., needed for the equipment, were available as were White Pine technical personnel familiar with performing experiments in the underground environment. Also, the rock structure and exposed surface geometry were more like those of a working mine area than could be found in a surface quarry or simulated in the laboratory. Figure 2 depicts the data collection area.

Because of the fault, the tunnel makes a right angle turn at this point after penetrating approximately 8 feet beyond the fault. The fault is thus exposed on the back, ribs and floor, and there is a large, undisturbed rock mass beyond the fault. The holes for the source and the sensor were drilled into the tunnel floor (Figure 3). Four hole pairs were used, located nominally at distances of 4, 8, 12 and 16 feet from the fault. The plane

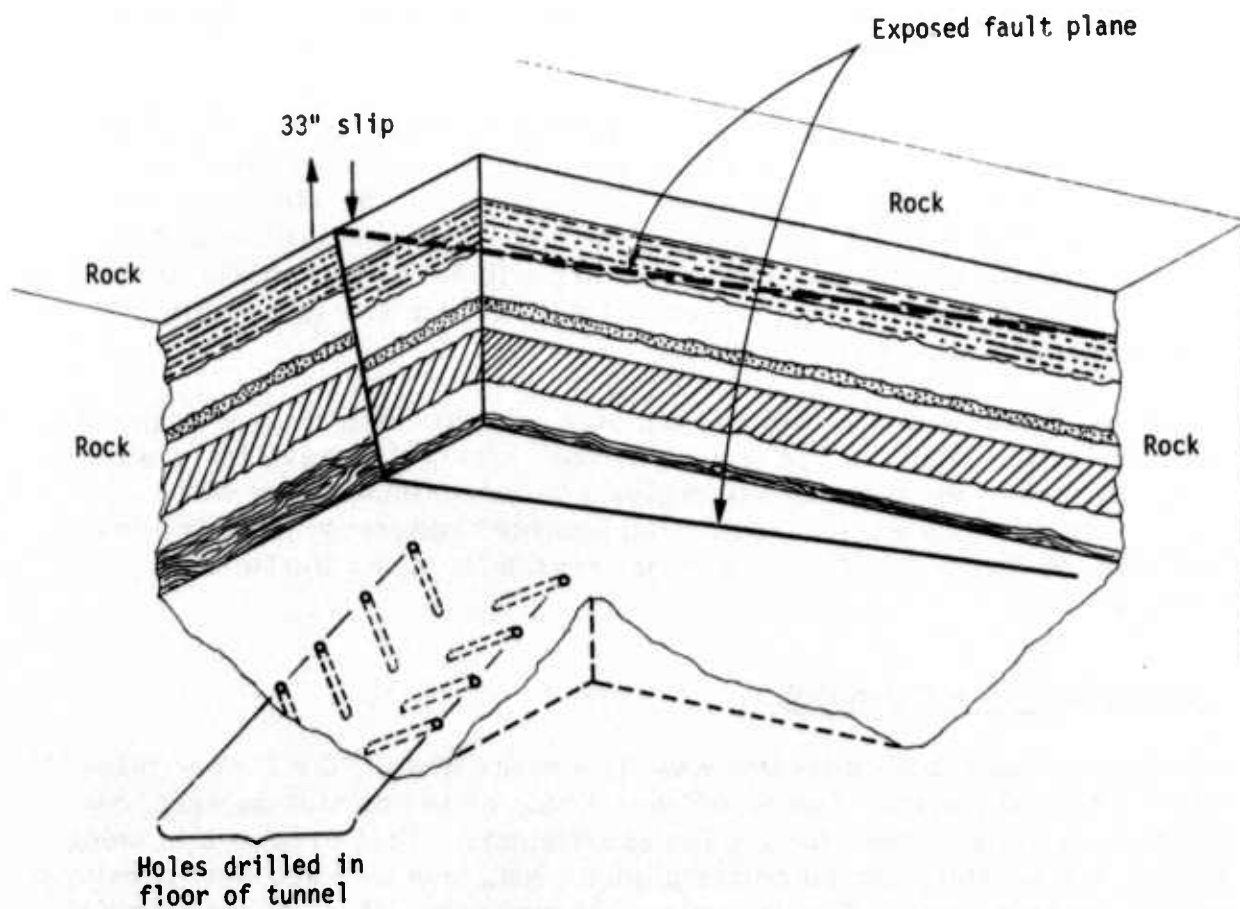


Figure 2. Cutaway View of Experimental Area.

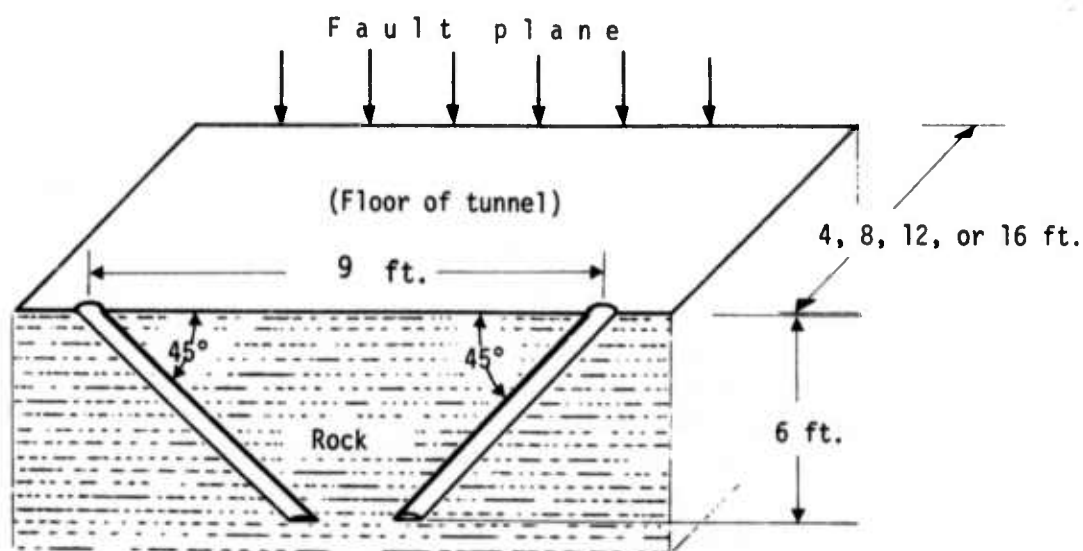


Figure 3. Nominal Arrangement of Test Hole Pairs.

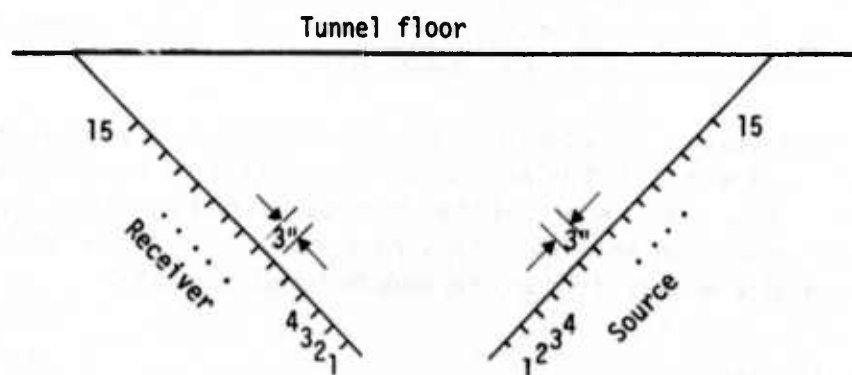


Figure 4. Nominal Source and Receiver Locations.

defined by each hole pair was intended to be perpendicular to the tunnel floor and therefore not parallel to the fault. The actual holes were drilled manually by White Pine technicians and were put surprisingly close to the nominal positions and orientations. Each hole pair was slightly non-coplanar, but this did not interfere with the experiment. (On the contrary, it makes the experiment more realistic.)

The experimental equipment is described in detail in Reference 3. A brief description is given here. The acoustic pulse was made by discharging a capacitor (charged to approximately 2000 volts) across a spark gap submerged in a hole filled with water. The reflected energy was detected by an accelerometer placed in the other hole. The received pulse was amplified, and a 4.5 ms signal interval was recorded and stored by the transient recorder. This part of the pulse was then output to a display unit that displayed it as an intensity modulated vertical trace on an oscilloscope. The trace was photographed for permanent record.

The majority of the experiments were performed using 15 source positions and 15 sensor positions. Figure 4 shows the nominal arrangement. The data collection procedure involved positioning the source and the sensor, discharging the source, recording and displaying the received signal interval and photographing the display. This was done for each of the 225 pairs of source and sensor positions. The line displays were recorded on adjacent line positions on film. Figure 5 shows the nominal structure of the film record. For each sensor position there are 15 adjacent lines corresponding to the 15 source positions, and there are 15 such groups of lines corresponding to the 15 sensor positions.

A horizontal slice across all 225 lines represents the received signal amplitudes at one time at the 225 positions of the equivalent rectangular sensing array. Thus the movie display is constructed by taking successive time slices and arranging each as a 15 x 15 square. This movie then shows the developing sound field at the sensor/source plane.

Experimental Results

The received sound field, shown by the movie format, shows the direct wave and the reflected wave. It also shows equipment noise and resonances in the equipment and the rock. The latter signals and effects distort and mask the reflected signal, and a significant amount of processing and filtering were needed to make the reflected signal apparent to the eye.

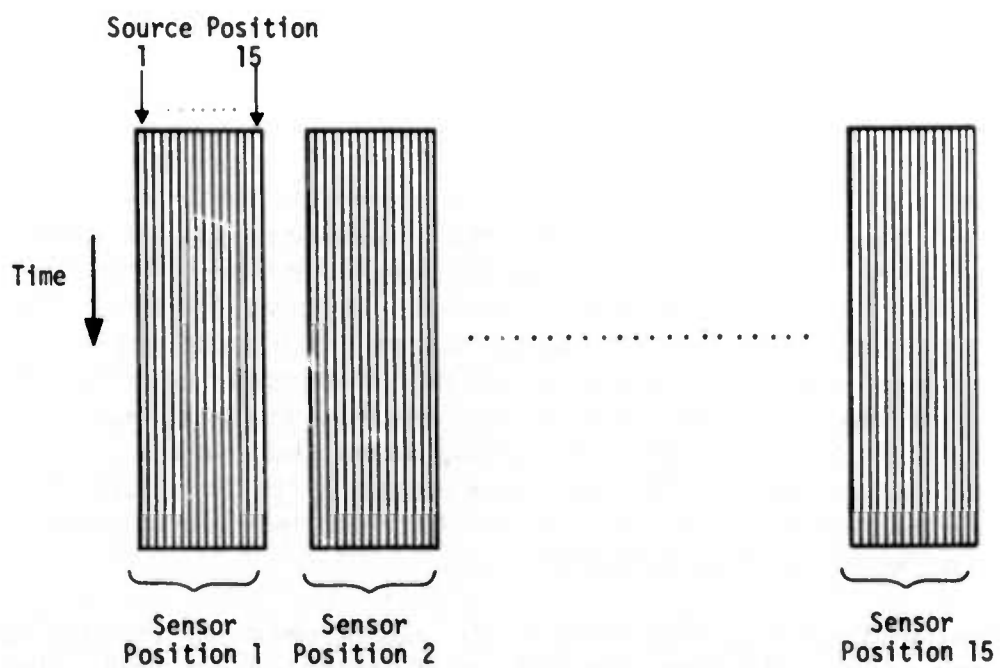


Figure 5. Nominal Film Recording Format.

Of 15 complete recordings, (i. e., format of Figure 5) made using four different hole pairs, only one record, from the hole pair located 4 feet from the fault, showed the reflected wave. The computer processing needed to make this reflected wave visible is described in Section IV. The remaining recordings, made from the same hole pair and at the 8 ft., 12 ft. and 16 ft. hole pairs, all show the direct wave, but the reflected wave was too obscured to be made visible in the movies.

The inability to detect reflections at 8 foot and larger ranges appears partly due to equipment limitations and partly to the experimental procedures. Both were modified according to the experience gained during the underground testing, but the final results, and therefore the final changes, were not known until after the testing was completed. Source power and sensor sensitivity do not appear to be controlling factors in receiving the reflected wave. The limits seem to be mainly in equipment induced distortion, the received signal bandwidth, film recording limitations and resonance phenomena. The computer signal processing was mainly devoted to compensating for these factors. The signal processing could be incorporated in the data collection equipment to improve the recorded data and thus potentially increase the fault detection range.

In addition to the fault detection results, the underground experiments encountered two additional phenomena that are of peripheral interest. One was the reception of microseismic signals in the 5 kHz-20 kHz band during a period when rock falls and roof cave-ins occurred in the mine. The other was the apparent reception of hydraulic shock impulses from a machine located 150 feet from the sensor. A description of these observations is given in Section IV.

SECTION II

DATA COLLECTION

A. Environment and Equipment

The part of the White Pine Copper mine used for the data collection effort is a portion of the mine reserved for experimental work. It is, therefore, free of most of the problems that one would encounter in a normal working mine environment. The air supply to the experimental portion of the mine came directly from the surface into this area of the mine. The air was thus relatively clean and dry. There was very little water seepage through the rock near the area that we used, and the area in which we were working was very dry. Dust was a great problem only when there was some experimental blasting going on or when we were cleaning up some of the surface rock from the working area. The 110-volt power was supplied by two separate 150KVA transformers. Except for the light bulbs that illuminated the area, ours was the only equipment that was regularly connected to these transformers. This area was perhaps as close to the laboratory environment as one could encounter in an underground mine.

In spite of these near ideal conditions, the equipment and procedures designed for and developed within the laboratory environment encountered problems when they were operated in the mine. These problems and recommended or suggested solutions are described in this section.

1. Power Fluctuations and Noise on Power Lines

The AC power supply was a two-wire system with no ground. At times during the experimentation we encountered large amplitude 60-cycle noise in the power supply. This problem was partially solved by driving a brass stake into the ground, covering it with large amounts of rock and wetting this down to provide a common ground for all of our equipment. However, this did not remove all of the large amplitude 60-cycle, and patience was the main solution to the 60-cycle problem. We never did identify the cause of the 60-cycle noise. Another problem was encountered when both the spark source and the data recording equipment were operated from the same 150 kilovolt ampere power transformer. When the power source was triggered under these conditions, a large amplitude transient was transmitted through the power lines into the recording equipment. This would show up in the recorded output as an excessively large and long lasting

transient pulse. This pulse would obscure a large part of the 5 milliseconds of signal that we were recording. In our situation this transient was avoided by supplying power to the power source from one transformer and operating the rest of the equipment from the other transformer.

At times during our data collection, drilling in preparation for explosive charges was done in the area near where we were operating. The drills were operated from an air compressor which was, in turn, operated from the same power transformers that our equipment was using. At these times there were large amplitude harmonics of the basic frequency of the air compressor showing up in the outputs of our recording equipment. The only solution we found for this problem was to wait until the air compressor was turned off. However, this particular source of noise did not appear in the recorder outputs at all times when the air compressor was operating.

All of these power line noise problems could be solved very easily by providing an isolation power source between the main power lines and the recording and spark source equipment.

2. Problems in Using Holes Drilled in Rock

Our experimental setup required that two holes be drilled into the rock. One of these holes was filled with water, and the spark source was discharged inside of this hole. There were two problems encountered with this water-filled hole. One of them was that the rock in which the hole was drilled contained small cracks through which the water would leak. Therefore, a relatively plentiful supply of water was necessary to refill the hole continually during the data collection process. A second problem was that the water filling the hole has to be relatively free of iron oxides and suspended particulate matter. When muddy or rusty water was used, the spark source was discharged at a lower voltage than was desired, thereby producing a smaller impulse than was planned. If this data collection procedure were to be used in the commercial mining environment, the best solution for both of these problems would probably be to carry four or five gallons of fresh water to the data collection area when the data collection is to be done.

The alternatives of finding a portion of the floor or ribs free of cracks or using some chemical compound to seal the cracks in the rock both appear to be impractical.

The accelerometer used to receive the transmitted signals was located in the second hole drilled into the rock. This accelerometer was held against the wall of the hole by an inflated rubber tube. (Details of this device are shown, ref. 3.) This accelerometer was positioned within the hole by a plastic tube which served the additional function of conducting the air pressure that was used to expand the rubber tubing. It was found during the experiments that the orientation of the accelerometer within the hole had a significant effect upon the amplitude and the phase of the received signal. During the major data collection experiments, an attempt was made to position the accelerometer so that the conducting cap was always facing toward the fault under investigation. To do this, it was necessary to bring the transducer back to the top of the hole each time that it was moved and verify that it was in the correct orientation. Due to the nature of the tubing on which the accelerometer was mounted (this tubing was rolled up), it was a relatively difficult problem to insure that the accelerometer maintained its correct orientation while it was pushed 45 or more inches into the receiving hole. This use of flexible components for a device that had to be oriented in a particular direction was not ideal. For commercial application it is recommended that a rigid mounting such as a long aluminum rod be used to hold the accelerometer so that it could be oriented properly. The rubber tubing experienced its own problems inside the hole. This tubing had to be replaced four times during the experiments because it ruptured either from the pressure or from the protrusions in the rock. This, of course, would interfere severely with use in a commercial mining operation. The suggested solution for this is to use a mechanical device to hold the accelerometer against the wall of the receiving hole. A number of such devices are currently in use for mounting seismometers in holes drilled in rock.

3. Spark Source Life

The spark source used for these experiments was estimated, before these experiments, to have a lifetime of 300 to 400 discharges at approximately 2,000 volts. During these experiments severe pitting and erosion of the spark gap was discovered at the 300 to 400 discharge level. One of the spark sources was operated for about 1,500 spark discharges, and it still produced a spark. However, the experimental results indicate that, even during the taking of one frame involving approximately 300 discharges from the spark source, there were significant changes in the shape of the energy pulse produced by the spark source. During the experiments it was noted that erosion began to appear at the spark gap after about 25 to 50 spark discharges; and once erosion appeared at a particular point on the

gap, it seemed that later discharges would also occur at the point where this initial erosion had taken place. Successive firings then erode more and more of the material as well as the insulating material in the spark gap until a deep pit of 1/4 inch or more occurred in the spark gap after 500 to 700 discharges. Attempts were made to file and sandpaper the original eroded area to retard the rate of erosion. However, these were not successful. A major drawback with this spark gap design is that it allows no way of adjusting the spark gap to compensate for erosion. It is possible that a spark gap design similar to that used in automobile spark plugs might be more successful in counteracting the effects of erosion due to successive firings.

Also during the final data collection trip, the spark source failed to operate properly when the juncture between the rubber insulation on the cable and the fiberglass mounting of the spark source separated due to the repeated flexure encountered during operation. This allowed water to seep into the mounting for the spark source and caused a discharge within the mounting rather than across the spark gap. Epoxy cement had been used originally for the seal between the rubber and the fiberglass. To cure this problem we used a silicone rubber adhesive which is flexible and covered this with plastic electrical tape. Water seepage around the O-ring seal was also a problem at one time. When the O-ring had become slightly worn, water could seep into the spark source mounting. This problem was cured by using silicone lubricant to seal the O-ring.

4. Dust, Humidity, and Temperature Problems

The only piece of equipment that encountered any problem with the dust in our area was the shutter of the camera used to record the transient sweeps. This shutter operated about 5,000 times without any problems. However, during the final data collection trip, it began to stick open. The camera repairmen diagnosed that it suffered from a combination of dust (which he found while attempting to clean the accessible portions of the shutter), humidity, and low temperature. Temperature ranged from approximately 50 to 60 degrees F, and humidity from 60 to 80 percent. In addition to cleaning the accessible portions of the shutter, he recommended that we keep the shutter in a warm, dry place when not in use and that we warm the shutter during use by suspending a light bulb below it to allow the warm air currents to pass over the shutter. His theory was that the fine lubricating oil on the shutter had become stiff with the low temperatures, and this, in connection with the dust in the mine, caused the shutter to stick. Also, he conjectured that the low temperatures in the mine lessened

the tension in the spring driving the shutter, causing it problems in overcoming the extra friction caused by the dust and the humidity. After the cleaning and with the lighted bulb suspended below the shutter, it continued to operate without additional malfunctions for approximately 2,000 more cycles during the final data collection trip.

The solutions to this problem in a commercial environment would be a periodic cleaning of the shutter and perhaps enclosing the shutter in a plastic drape to keep dust away from it and to keep excessive humidity away from it during short periods of operation.

The transient recorder and/or the transient recorder display seemed to suffer from the low temperature in the mine. Each day this equipment was plugged in; the power was turned on, and the equipment was allowed to warm up for approximately 1-1/2 hours before the actual data recording was begun. A rough calibration was performed when the equipment was turned on, and the calibration was repeated approximately 90 minutes later. Calibration in every case was found to have changed greatly. The calibration was also checked frequently during the daily operations. It was found that equipment continued to drift during the first five hours of its operation, and after the fifth hour the drift would cease. It was deduced that this drift was due to the equipment warming up and perhaps from humidity, that had accumulated during the night storage in the mine, being driven off. If the equipment had been stored in a warm, dry room on the surface and brought down into the mine for data collection each time, this would probably have been no problem.

The original film planned for use in the mine was Polaroid Type 55PN. This film was used during the preliminary experimental trips and was also used during the first data collection trip. However, whatever the cause, the film was discovered to be unsatisfactory in the mine environment. During all of the surface laboratory testing this film was quite satisfactory. However, when the film was used in the mine a number of problems were encountered.

- 1) The film could not be developed properly in the mine probably because of the low temperature and the fact that the developing gel did not spread evenly.
- 2) When the film was carried to the surface after being exposed in the mine and attempts made to develop it on the surface, it was not possible to remove the film from the film case without

developing it. This was probably caused by a swelling of the paper enclosure due to the high humidity in the mine.

Rather than attempt to find a way around these problems with a Polaroid film, the solution was to use preloaded film packs with 3 x 5 Kodak film, Type 6127. Three film packs were used during the experimenting. These were loaded in the dark room before going on the data collection trip, and a changing bag was brought to the mine so that extra film could be loaded during the experimenting. This was found entirely satisfactory. If this procedure was used in a commercial operation, of course, the film packs could be loaded at the surface and brought down to the experimental site.

The trigger circuit on the transient recorder also appeared to suffer from the temperature and/or humidity of the mine environment. This trigger circuit worked without any problems in the laboratory. However, when operated in the mine, it did not trigger the transient sweeps consistently at the same place. This caused numerous problems that will be described in more detail in the section on data processing. This problem could probably be circumvented by driving the transient recorder synch with a Schmidt trigger.

The final problem to be mentioned is an overall problem meant to cover all the other difficulties that did and may occur in the use of laboratory equipment in the working mine environment. It was found that, even though all of the equipment was apparently working (the spark source firing and the transient recorder triggering), there were still numerous cases when the recorded signal was not reproducible--even though the receiver and the source were in exactly the same positions and the voltage was unchanged. During the normal operation there would be a relatively continuous change in the shape of the received waveform as the source was moved from position to position. At times, however, it was noted that a signal did not appear to be similar to the previous signal. In order to monitor this, an oscilloscope was attached to the transient recorder, and the received waveform was displayed, on an XY scale, on this oscilloscope. In the cases when the received waveform appeared to be anomalous, the transient recorder was again reset without recording that shot on film, and the shot was refired. This was continued until we obtained two successive waveforms that were sufficiently alike. We were not able to determine the cause of the anomalous waveforms. In some cases it was due to faulty triggering. In some cases it was probably due to external triggering at the wrong time. However, the majority of the anomalous waveforms remained unexplained. The best cure for this problem is to use an

oscilloscope to monitor the waveforms as we did and to observe a continuous or near continuous change of received waveforms from one source position to the next.

B. Geology

The experimental area was located within the Upper Keweenaw Series in the White Pine District at the bottom of the Nonesuch Shale. Figure 6 shows a cross section through the drift. The rock surface on which we worked was approximately at the 0' level in Figure 6. This is the top of the the Copper Harbor Conglomerate into which the test holes were drilled. Figure 7 shows the geometry of the fault that was being studied. A fractured rock zone extended one to two feet on either side of the fault.

Figure 8 shows the locations of the holes drilled for these experiments. This figure also shows the names (1L, 1R, X, etc.) that were used to denote the individual holes. These names are used in the test of this report.

Figure 9 is a scale drawing of hole pair 1 projected onto the plane of the fault. This and Figure 10 were drawn from measurements made at the site. The ideal 45 degree angles were not obtained, but this did not interfere with the experiment or the interpretation of the results.

Figure 10 is a scale drawing, perpendicular to the fault, showing the actual angles made by the two holes of hole pair 1. The parting shale location is also shown on the downside of the fault. This shows that the transmission was through the Copper Harbor Conglomerate (sandstone), and the reflections probably were from the parting shale.

A number of values are available for the compressional and shear velocities. In a letter report to Mr. L. A. Garfield (ref. 4), shear velocity values of 10,200 to 11,200 ft/sec and longitudinal velocities of 14,200 to 18,600 ft/sec are listed. These velocities were determined from sample cores taken from the Nonesuch formation. The values given for the sandstone at the base of the formation were $v_p = 16,500$ and $v_s = 10,200$.

Another investigator, using an 8 element seismic array operating at 7 Hz, reported average values of $v_p = 16,000$ and $v_s = 10,000$ over a 15-mile path in the White Pine area. In our experiments, measurement of first arrival times for pulses recorded in the 5 kHz - 20 kHz band gave values of v_p in the 15,000 - 17,000 ft/sec range.

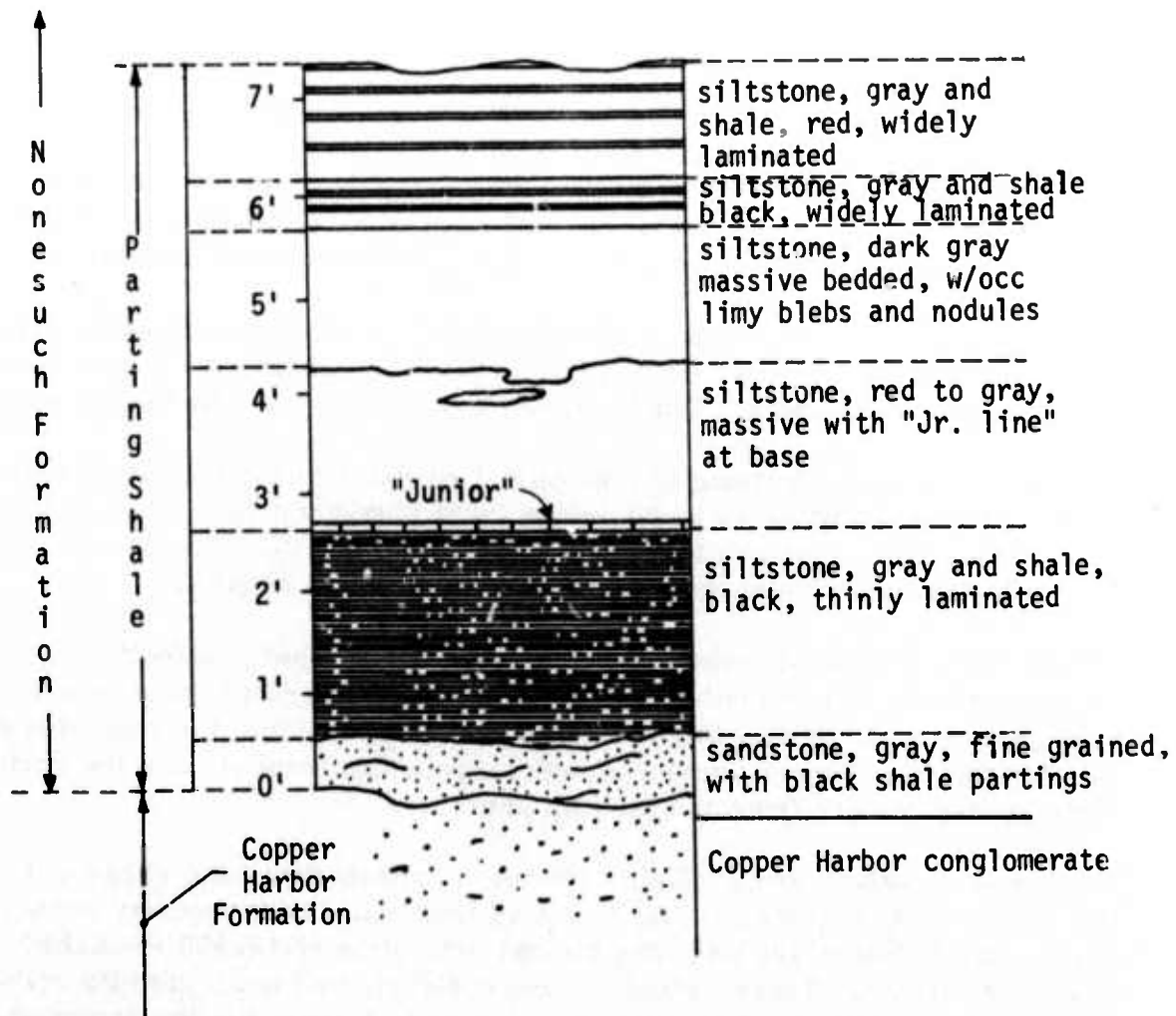


Figure 6. Geology of Ore Column in the Experimental Area.

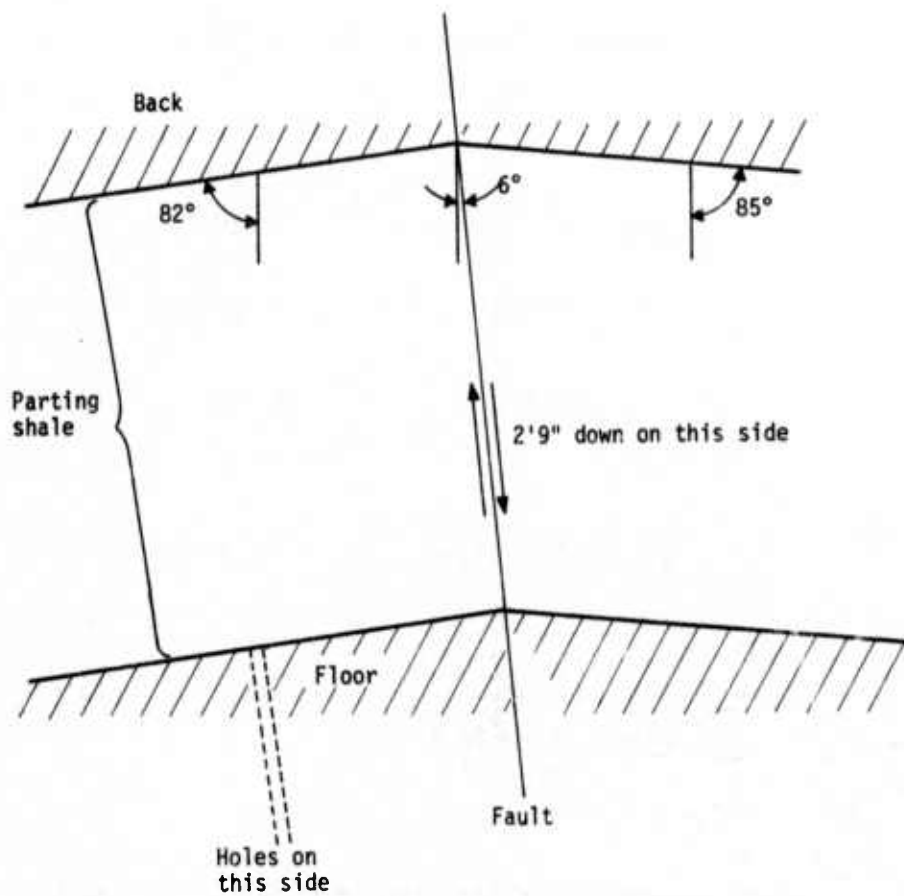


Figure 7. Geometry of the Fault.

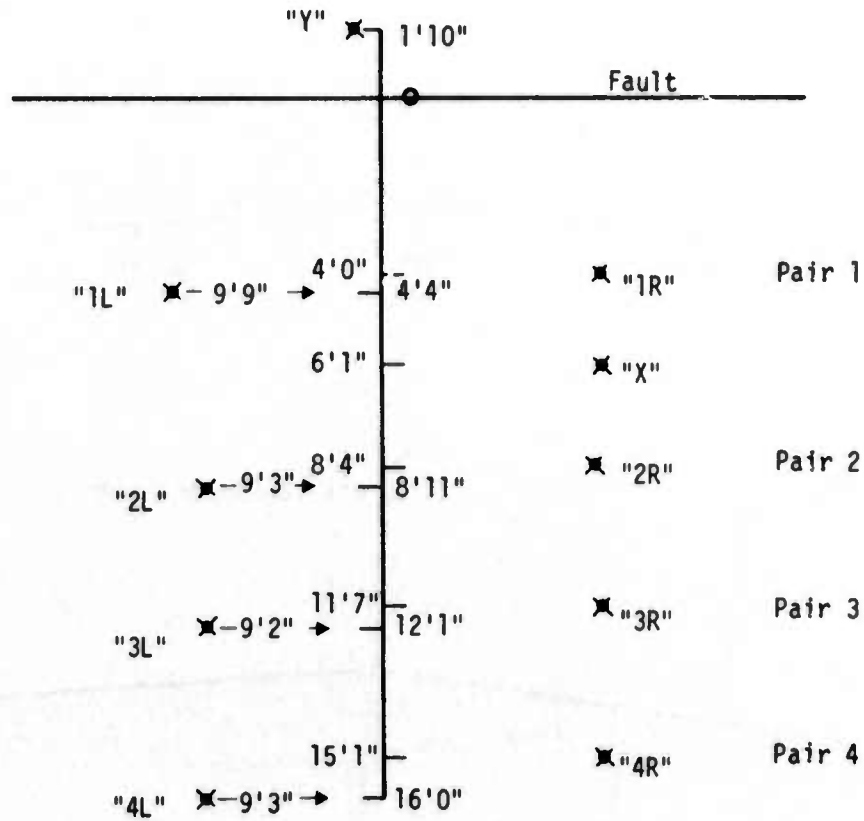


Figure 8. Locations and Names of the Test Holes.

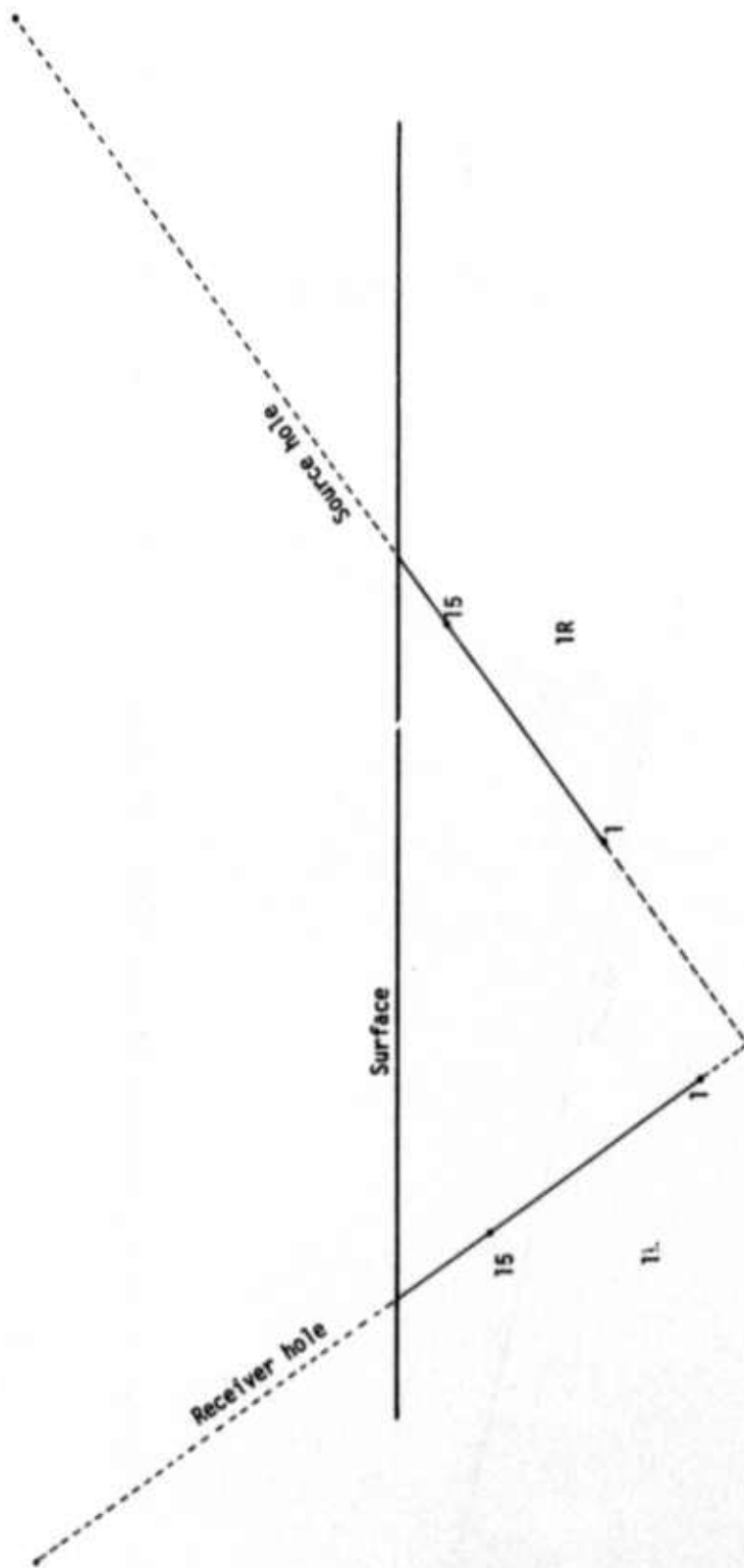


Figure 9. Scale Drawing of Hole Pair 1 Projected onto the Fault Plane.

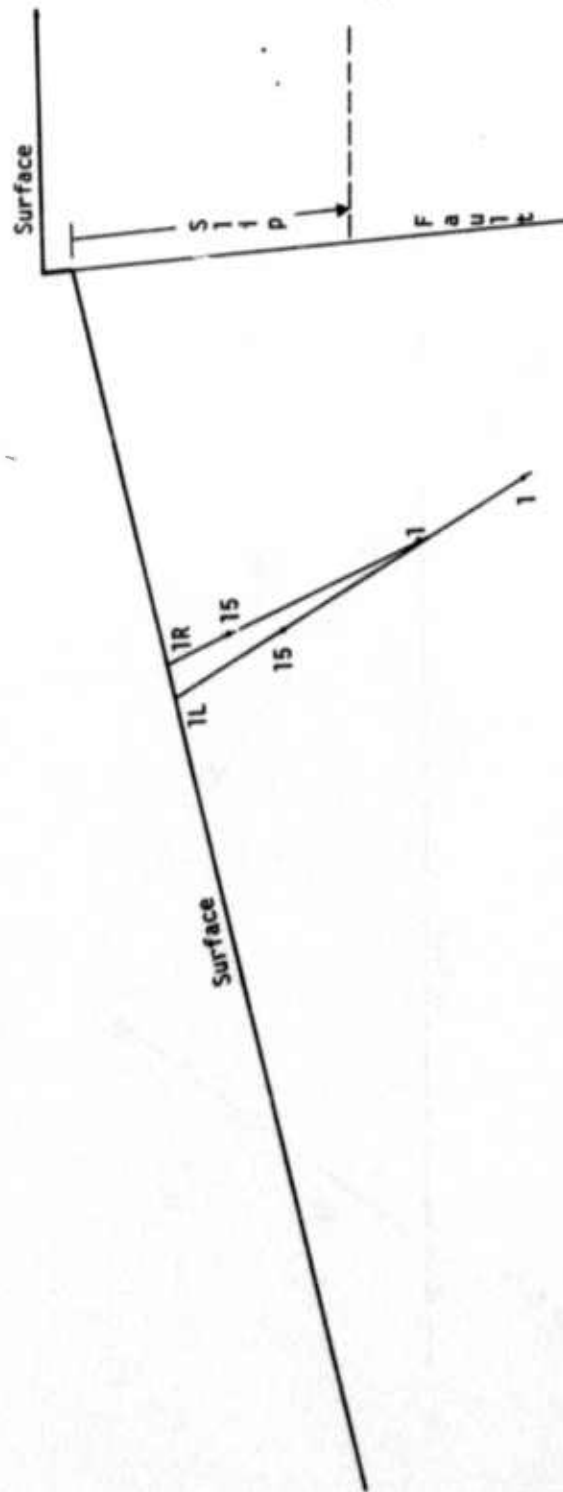


Figure 10. Scale Drawing of Hole Pair 1 Projected onto a Plane Perpendicular to the Fault.

SECTION III

DATA PROCESSING

A. Raw Photograph Structure

The output of the accelerometer was captured by the transient recorder and displayed as an intensity modulated trace on the associated display unit. The successive traces corresponding to different pairs of positions of spark source and accelerometer/receiver were recorded on film. Details of this procedure and the rationale for it are given in the previous technical reports.

This section will discuss the ideal structure of these photographs and the problems encountered in attempting to obtain the ideal photograph.

1. Ideal Photograph Structure

The original plans for displaying the recorded transient data were to use a fiber optic viewer that would transform the intensity modulated trace into a succession of patterns representing the passage of the transmitted and reflected sound waves through the plane of the transmitter and receiver holes.

The majority of the experiments were performed using 15 positions for the spark source or transmitter and 15 positions for the accelerometer/receiver. These positions were spaced 3 inches apart. Each experiment with a particular pair of holes thus involved 225 pairs of positions for the source and receiver.

The data format plan for using the fiber optic viewer placed the photograph signal traces in 15 separate bands on the film. Each band corresponded to one position of the receiver and consisted of 15 separate lines or traces, each corresponding to the intensity modulated trace obtained from one position of the transmitter. The adjacent traces were spaced on the film in such a way that there was a slight overlap. The adjacent bands were separated by a large enough space on the film so that they could be readily identified.

When it was learned that the fiber optic viewer could not be constructed within the time of the contract, the display procedure was changed. The

new procedure involved digitizing the film with a scanning microdensitometer, transforming the photographed traces into the desired movie format by means of a digital computer, and finally writing the successive movie frames onto film. To allow for linearization of the film density versus accelerometer voltage curve, the film format was changed to incorporate a sequence of calibration lines. (See Figures 13 and 14.) The calibration lines were produced by triggering the transient recorder while a standard calibration voltage was placed on the input. These calibration lines would also allow corrections for film, camera, and equipment variations that would produce a non-uniform film trace for a constant voltage input. Additional calibration lines were also included on the film between bands 5 and 6, between bands 10 and 11, and following band 15. These would allow correcting for drift or time variations in the equipment, film, etc. These calibration measures resulted in a somewhat more complicated film format than originally planned, but it was felt that the protection from possible errors was worth the added effort. The computer processing was then designed to work with the ideal data format or a reasonable approximation thereof.

2. Photographs Produced During the Experiments

A great many factors combined to make it very difficult to produce the ideal photograph structure. Most of the problems occurred because of the natural human errors involved when two people repeat a single operation 200 - 400 times over an extended period of time. Attention tends to wander during repetitive, boring tasks and so errors occur. In addition to the human errors, there were also problems with the equipment. These included the natural drift of the equipment during the warm-up period and unexplained variations in the equipment performance from day to day.

The film recording for each experiment involved approximately 250 to 275 separate exposures. To keep track of which exposure was being performed, a log book was kept. The planned exposures were numbered successively in this log book and following the number of each exposure was a description of what it should contain (calibration voltage value, source and receiver position, or blank film). A hand counter was also used to help keep track of which exposure was being performed at a given time. This doubly redundant system plus the memories of the two operators helped keep track, with a few errors, of which operations were to be performed during the two to three hours involved in each experiment. The errors that occurred, in spite of these precautions, were corrected during the digital processing. Such errors would have been very difficult to correct, however, had the

fiber optic viewer been used. There were a number of equipment settings made during the calibration procedure. These included the trigger level, trigger polarity, DC off-set, sweep time, and peak voltage. The controls for all of these settings were placed conveniently on the front of the transient recorder panel. Not so conveniently placed, but also on the front of this same panel, was a small micro-switch that allowed the transient recorder to be reset after a signal had been photographed. With the operational setup, all of these controls were located below the camera used to photograph the display, and thus the operator of the recorder and camera had to rely on touch to find the reset button and avoid bumping the other knobs. To prevent the settings being changed by inadvertently bumping the knobs, the knobs were all removed before going to the mine and so only the bare shafts protruded. However, the bare shafts could still be bumped, and this would cause small changes in the settings of the equipment. From a human factors standpoint, this was a very poorly designed control panel.

The camera shutter controls, the exposure time settings, and the f/setting were not so easily changed by accident. There is evidence, however, on at least one photograph of the aperture or the exposure time being accidentally changed. There was also one equipment construction error that caused difficulty with the film format. The film holder was moved between exposures by rotating a wheel through the center of which a threaded shaft passed. The gearing was such that one-quarter turn of the wheel would cause the film holder to advance the proper amount to place adjacent traces on the film with the desired amount of overlap. This wheel was notched at four places on its circumference, and a spring loaded detent rested against the circumference of the wheel. This detent clicking into place in one of the notches indicated that the correct quarter rotation of the wheel had been performed. However, one of the four notches was slightly misplaced on the circumference of the wheel (a matter of one or two degrees from the center of the wheel). This did not appear critical at the time that the wheel was constructed. However, when the photographs were produced, it was found that the film holder advanced slightly more than it should have in this detent position. This caused a slight underexposure of the overlap between these two adjacent lines. This slight underexposure produced a very noticeable herringbone pattern in the final movie format. This herringbone obscured the patterns that were sought in this movie, and it had to be eliminated during the computer processing.

The problems encountered in attempting to obtain a chosen format for the data recording pictures could be minimized or eliminated by proper equipment design, as would be done if the device were to be used commercially

in a mining operation. Functions, such as resetting the trigger, film advance, and calibration, could be performed automatically and thus eliminate the possibility of human error. However, for an experimental setup such as this, there was no opportunity or justification for this degree of sophistication.

B. The Digitizing Process

The recorded signal photographs were digitized by a scanning microdensitometer. This computer controlled device, manufactured by Optronics, Inc., is able to digitize transparencies into either 64 or 256 density levels. The transparencies are scanned in a 25 micron, 50 micron, or 100 micron wide line with the average transmission density of each square element along this line being digitized and eventually written onto magnetic tape. Each scanning line results in one record on the magnetic tape.

Our signal recording photographs were scanned in a direction perpendicular to the signal sweep images. Thus each scan line ideally will correspond to one time. The movie format desired for display of the received acoustic signals could, therefore, be produced by merely stacking the scan values of 15 bands in each photograph. The direction of the scan thus corresponds to the different positions of the spark source, and the perpendicular direction corresponds to the 15 positions of the receiver. In digitizing the experimental photographs, the 100 micron scan line width was used. With this selection each 5 millisecond sweep was approximately 357 scan lines wide. Thus each scan line corresponds to 12 microseconds, or the scan lines correspond to a time sampling rate of 71,600 samples per second. Therefore, the 5 kilohertz to 20 kilohertz passband used in recording the information should be represented quite well. For amplitude quantization the 64 intensity levels were chosen. This produced a good representation of signal waveform shapes. To check the fidelity of the digitization process, a number of the digitized photograph tapes were used to produce photographs that were then compared with the originals. With the 100 micron sample size in the 64 levels of intensity, the original and the reproduced photographs were practically indistinguishable to the eye.

This method of digitizing was quite similar to the procedure that would have been used had the fiber optic viewer been constructed. However, the 100 micron scan line width had a finer resolution than the fiber optic viewer would have had. Since each scan line eventually results in a movie frame representing the sound intensity field at one time, it is necessary that the

photographed images of the transient recorder sweeps be precisely aligned on the photograph. Ideally this alignment should be within 100 microns on the film. However, considering the frequencies involved, an alignment error up to 300 microns could probably be tolerated. The actual misalignments (thought to be due to the transient recorder trigger circuitry operation variability) were between 200 microns and 800 microns for adjacent sweep images. Attempts to produce the movie format from raw data photographs with this amount of misalignment resulted in failure. This misalignment was later corrected during the digital processing of films.

C. The Need for Editing of the Digitized Photographs

The trigger misalignment was only one of the problems that interfered with seeing the desired patterns in the movie representation of the film. The herringbone pattern mentioned earlier, the low frequency components (less than 500 hertz), and drastic errors in film exposure were other problems that also occurred. To remove these kinds of noise from the imagery, it was necessary to work with the time waveforms that were represented in the photographed images. Since the original films had been scanned perpendicular to the time direction, it was therefore necessary to transpose the digitized tape so that each record in the transposed tape represented one time sweep or one exposure on the original film. The alternative would have been to have the original photographs scanned in the direction desired for this extra process. However, this was an expensive process, and because of problems with the Optronics equipment, this was also a very time consuming process. In addition to the cost and time involved, it would still have been necessary to transpose from the time scan direction to the movie scan direction in order to produce the movies. Therefore, a computer program was written that could transpose a 900 x 900 point digitized photograph image. This program was used to transform the original digitized imagery into the time scan direction imagery used for the editing and then transpose the results of the editing process into the movie scan imagery.

To clean up the transposed image tapes, an interactive computer program was written, operating on the XDS 9300 computer using the Tektronix storage tube display unit for output and signal display. This program was able to fetch and display on the oscilloscope any desired signal sweep on the digitized transposed tape. In addition to displaying the digitized signal waveform, the program was also able to shift the waveforms, amplify the signals, change the signal DC level, delete signal waveforms, and copy

signal waveforms either before or after editing onto an output tape. Two modes of display were available: one of which displayed 200 sample points on the scope and was used as a high resolution output; the other of which displayed 500 points and could thus be used to observe the entire signal waveform. The normal mode of operating this program was to display sample waveforms taken from the transposed digital tape and experiment with the editing parameters. Many different filters and other signal modification techniques could thus be tried on sample waveforms, and when the parameters were discovered that produced the desired result on the waveforms, the program was then placed into an automatic mode of operation and the entire digitized tape would be automatically processed. The processed result would be placed onto a separate output tape. This output tape would then be transposed once again, and the transposed tape would then become the input to the movie-making program.

D. Realignment of Signal Sweeps

A number of causes evidently combined to produce the misalignment in the photographed signal sweeps. One of these was probably the normal variations in the transient recorder trigger circuit response. Another is the spark gap erosion that occurred after a spark source had been fired a number of times. This erosion would change the path of the discharge and would thus affect the shape of the current waveform during discharge and would produce a corresponding change in spark gap trigger output. These two conditions would primarily affect the alignment when the transient recorder was used on internal trigger. The transient recorder was also operated in the external trigger mode, and misalignment was also found in this mode. In this mode the trigger circuit variation would, of course, cause problems. In addition to this, there would be the effects of the transmission path. These would change the shape of the received pulse as the spark source and the accelerometer positions were changed. In both cases it was found that the trigger pulses, and the initial pulse in the case of the external trigger, varied greatly across the sweeps recorded in each of the experiments.

A number of different techniques were tested to realign the signal waveforms in each of the experimental photographs. One method was to establish an arbitrary signal value somewhere near the center of the 0 to 63 range of the digitized values and to shift all of the digitized signal waveforms so that the first crossing of the signal from negative to positive would occur at a selected time point. Another technique was to align the

first peak of each of the signal waveforms so that the first peaks all occurred at a chosen time point. These two alignment procedures were used and applied to both the raw digitized signals and to the digitized signals after they have been filtered. In all cases the imagery resulting from the alignment attempts showed approximately the same thing.

E. Time Filtering of Digitized Signal Waveforms

A typical raw waveform is shown in Figure 11. This is one of the waveforms that was obtained on the final data collection trip. It shows a slowly varying DC level that was probably due to the equipment. All of the equipment used during the experiments was AC coupled. The waveforms collected on the earlier trips did not show this DC level variation. The earlier trips concentrated primarily on low contrast photographs, while the final data collection trip concentrated on high contrast photos. The high gains that were needed to obtain the signals that would produce high contrast photographs may have saturated one or more of the amplifiers. This saturation could then have caused the DC level variation in response to signal pulse arrivals. Another feature of this signal is the presence of a 6 kilohertz pulse early in the signal waveform and a 12 kilohertz ringing pulse appearing later in the waveform. No experimental explanation for this phenomena was obtained, but the most probable explanation is that this is a filtering effect due to the rock. Also, in the waveforms produced when either the source or the receiver were near the rock surface, there is a persistence of a 12 kilohertz signal that lasts to the end and in many cases far beyond the end of the 5 millisecond sweep that was recorded.

The primary filtering performed on these digitized waveforms was a high-pass filter that was used to eliminate the slowly varying DC. Results of this filtering are shown in Figure 12 where the waveform in the previous figure has been filtered. High pass filtering produces a signal with a zero DC value. Since the photographic method of displaying the data does not allow for negative values, it was therefore necessary to introduce a DC bias after the signal had been filtered. The highpass filtering and the addition of the constant DC level for all signal sweeps was found to eliminate the herringbone pattern that appeared in most of the photographed imagery.

A number of filtering techniques were tried on the digitized signals. Recursive lowpass and highpass filters were the simplest to implement and so were tried first. However, recursive filters produce a phase shift that is frequency dependent. Since the primary source of information in

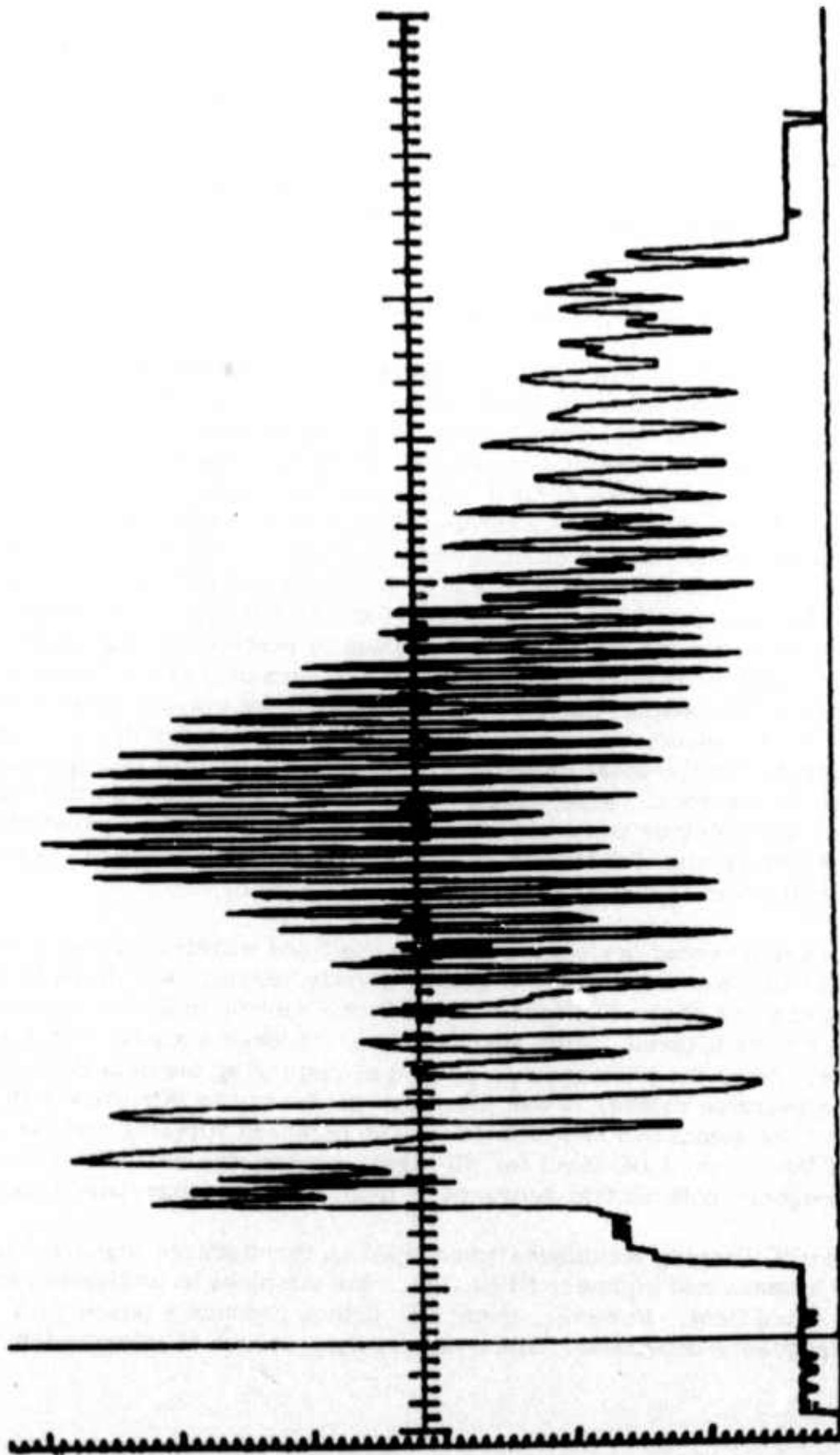


Figure 11. 500 Point Display of Digitized Sweep.

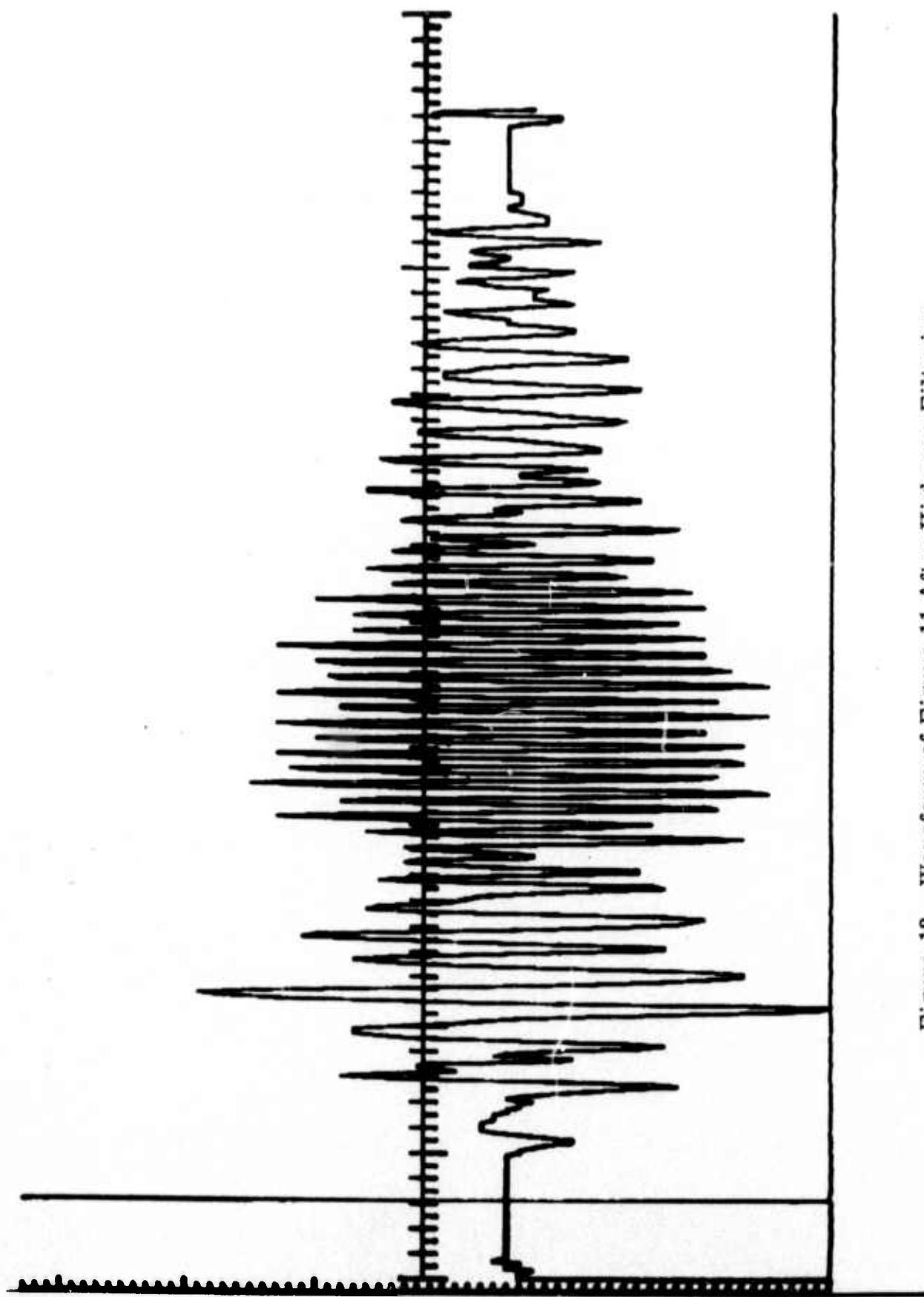


Figure 12. Waveform of Figure 11 After Highpass Filtering.

the signals is contained in the relative phase, the recursive techniques were abandoned in favor of two-sided averaging. The lowpass filter obtained by averaging the points on either side of the central point produces no phase shift, nor does a highpass filter that results from subtracting the lowpass filtered signal from the original. These kinds of filters can also be cascaded quite easily to produce filters with arbitrary order and arbitrary bandwidth. Figures 16, 17, and 18 show another signal and the results of bandpass filtering it with center frequencies of 12 kHz and 6 kHz.

SECTION IV

RESULTS

A. Analysis of Experiments

Table 1 is a summary of the photographs made during the data collection phase. Six of the photographs or frames were made to test calibrations, attenuation, transmission velocity, and equipment performance. Fourteen frames were the array type data records. In recording frames 1 - 6 the gains, scales, and intensities were set in such a way that the received waveform amplitudes were accurately recorded and could be recovered, without distortion, from the digitized film. This required using low gains, etc., to avoid having the peak of the direct wave saturate the transient recorder, display, and film. The rationale for this care was that the reflected wave might appear superimposed on the direct wave. In such cases accurate amplitude recording would be needed to extract the reflected wave. A side effect was that signal amplitudes, after the first direct wave peak, were so low that the quantization, during digitization of the photographs, distorted the movie outputs. Therefore, the later frames were made with high signal gain and with a transient recorder bias setting that produced zero display intensity for negative amplitudes less than 0.3X full scale. This resulted in a clipped signal being recorded on film. The clipped part of the signal was from 1 ms to 5 ms long, depending on how close the source and receiver were. Amplitude information was lost during this part of the signal, but the successful result indicates that this did not matter.

Figure 13 is an enlargement of frame 16 as it was recorded during the experiment. The various problems discussed earlier (extra bands, herringbone, flare, misalignment of trigger pulse) are all present in this frame. Band 0 was made using the external trigger, which was not operating properly. This band was not used for the data analysis. Bands 1 - 15 are the array recording and were made using internal trigger. A movie made from this frame, without processing, showed none of the expected features. Figure 14 shows frame 16 after the sweeps have been aligned by the first peak. (The sweeps were shifted in the computer so that the first maximum of the direct wave was in the same location in each digital record.) This alignment is not perfect, as the ragged appearance of the dark strip near the top of each band shows. (This is the peak used for

Table 1.

EXPERIMENTAL CONDITIONS AND EQUIPMENT SETTINGS
DURING THE DATA RECORDING EXPERIMENTS

Frame Number	Hole Pair	Size	Scale	Band	Voltage	Date	Comments
1	1	10x10	20 mv	1K-20K	2 KV	7/10/73	New hose needed 60 psi. Hose ruptured after third band.
2	1	"	"	"	"	7/11/73	Problems with power source not firing. Repairs made.
3	2	19x19	"	"	"	7/16/73	Shutter sounded odd during calibration band. Sparkgap cleaned after band 7.
4	2	10x10	10 mv	"	"	7/17/73	
5	2	"	20 mv	4K-20K	"	7/17/73	
6	2	15x15	10 mv	"	"	7/18/73	Nonuniform array used. 6" spacing on two outer lines. Accelerometer cap lost in hole, data collection terminated.
7	-	-	20 mv	-	-	11/14/73	Calibration only, to check new sparkgap and accelerometer cap.
8	4	15x15	10 mv	4K-25K	2 KV	11/14/73	Transient recorder scale was chosen to saturate on peaks.
9	4	-	200 mv	"	"	11/14/73	Calibration run. 2 bands. Accelerometer at 7 and 21, source positions 7 to 21.
10	3	15x15	100 mv	"	2.4 KV	11/15/73 and 11/16/73	To 2.3 KV on band 2, to 2 KV on band 6. Sparkgap failure during band 6. Water leaking into housing and causing short. Completed frame after repairs. Shutter sticking open at end of frame.
11	X-2	"	"	5K-20K	1.4 KV	11/17/73	New sparkgap used. Noise problems caused shutdown at band 6. Resumed after repairs to amplifier.
12	3	"	"	"	"	11/17/73	Problems with self-triggering due to microseismic activity.
13	4	"	20 mv	"	"	11/19/73	Still have self-triggering.
14	Y, 1R	-	"	"	1.4 KV	11/19/73	Test transmission through fault.
15	-	-	100 mv	"	"	11/20/73	Calibration test using new bias level setting.
16	1	15x15	"	"	"	11/20/73	Ignore first band, made with external trigger.
17	4	"	20 mv	5K-25K	"	11/20/73	
18	4	-	100 mv	5K-12.5K	"	11/20/73	Recording transmitted waveforms.
19	3	15x15	"	"	1.45 KV	11/21/73	
20	-	-	"	"	"	11/21/73	Final calibration test.

Comments on Table 1.

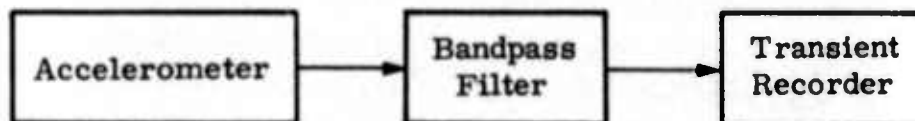
The following conditions apply to all frames except as noted in the comments

Recorded on Kodak commercial film Type 6127 at f 1.8 and $1/5$ sec.

The transient recorder sweep time was 5 ms/sweep.

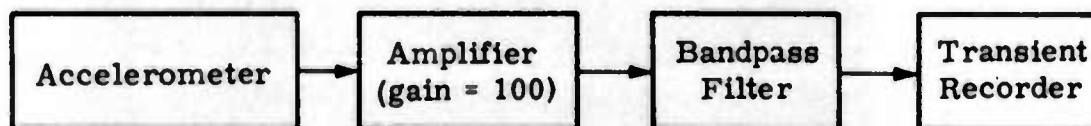
All signals were AC coupled.

For frames 1-6 the accelerometer output was input to a bandpass filter, and its output was input to the transient recorder.



Equipment Connections for Frames 1-6

For frames 7-20 a transistor amplifier (gain = 100) was inserted between the accelerometer and the bandpass filter.



Equipment Connections for Frames 7-20

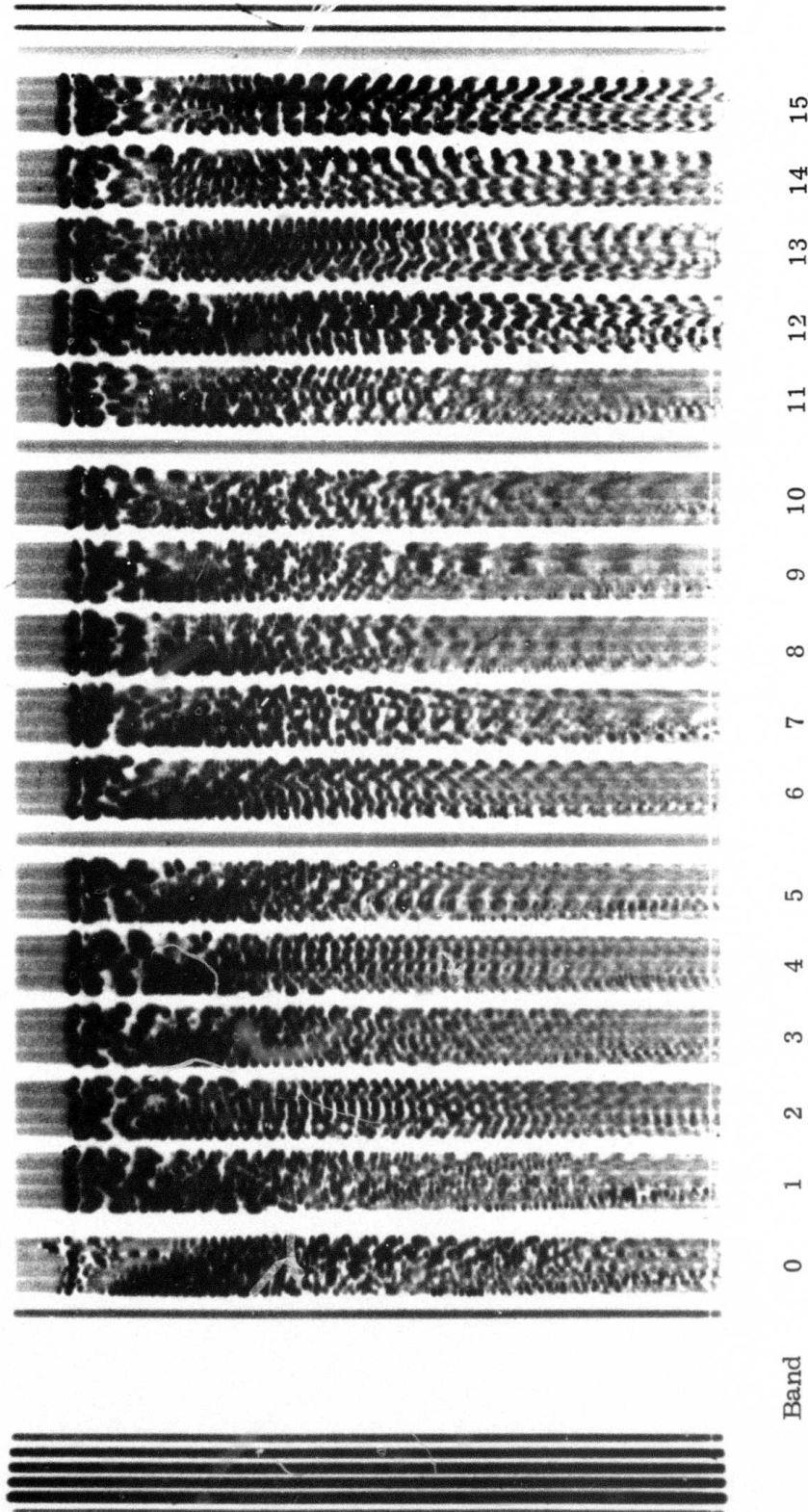


Figure 13. Frame 16: Data Recording from Hole Pair 1.

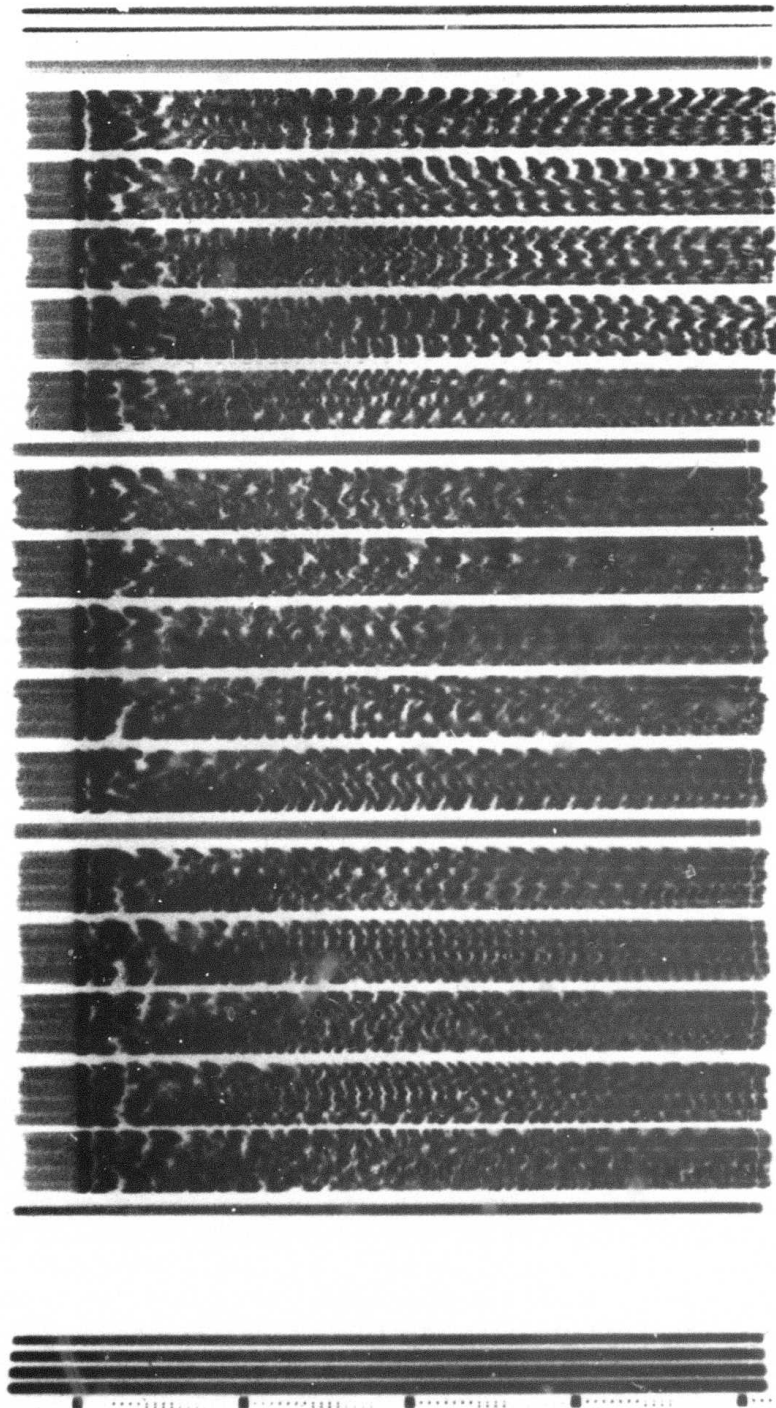


Figure 14. Frame 16 Aligned by First Peak.

alignment.) A movie made from this aligned version of frame 16, but with no other processing done on the data, showed dark movie frames corresponding to the first peak but no indications of any other direct or reflected waves.

Many different processing methods were tried (using the editing program) in an effort to get a movie that would show the reflected wave. The time waveforms showed large components near 6 kHz and 12 kHz, and, since we did not know which frequencies contained the desired information, the early attempts preserved the entire 5 kHz - 20 kHz frequency range that had been recorded. Broadly speaking, these methods were DC level shifting, extracting moving averages, highpass filtering, and amplification. None of these was successful. Figure 15 is a movie resulting from high-pass filtering of frame 16.

The second generation editing concentrated on the 6 kHz and 12 kHz frequency regions. Figure 16 shows the sampled time waveform for line 12, band 13. This is the 500 point edit display with each small interval on the time axis representing five samples or 70 μ s. The large DC level shift is a dominant feature of the unedited waveforms. The 6 kHz and 12 kHz components can be easily seen in the alternating negative peaks. Because they are simple to implement, the first kind of bandpass filter used was the recursive. Using recursive filters of various orders and bandwidths gave no positive results. The most likely explanation for their failure is that they introduce a phase shift that obscures or destroys the phase relations that would reveal the reflected wave in the movie.

The next bandpass filtering method tried used a modified Hamming window that does not produce a phase shift. Figure 17 shows the waveform in Figure 16 after being filtered in this way. The passband in Figure 17 is 8 kHz - 14 kHz. Figure 18 shows line 13 of band 13 (adjacent line to Figure 17) filtered through a passband of 5 kHz - 7.5 kHz. The former filter produced no results, but the later one gave the movie shown in Figure 19. This movie shows the direct p-wave, the direct s-wave, and the reflected s-wave.

In the following discussion of Figure 19, the individual frames are numbered starting with number 1 in the upper left corner, number 11 in the upper right corner, number 12 below number 1, etc., to number 176 in the lower right corner. Rows are numbered 1 to 16 from top to bottom. Each of the 176 frames is an array of .4 mm x .4 mm squares (pixels). Each frame is 29 pixels high and 28 pixels wide. In scanning the original

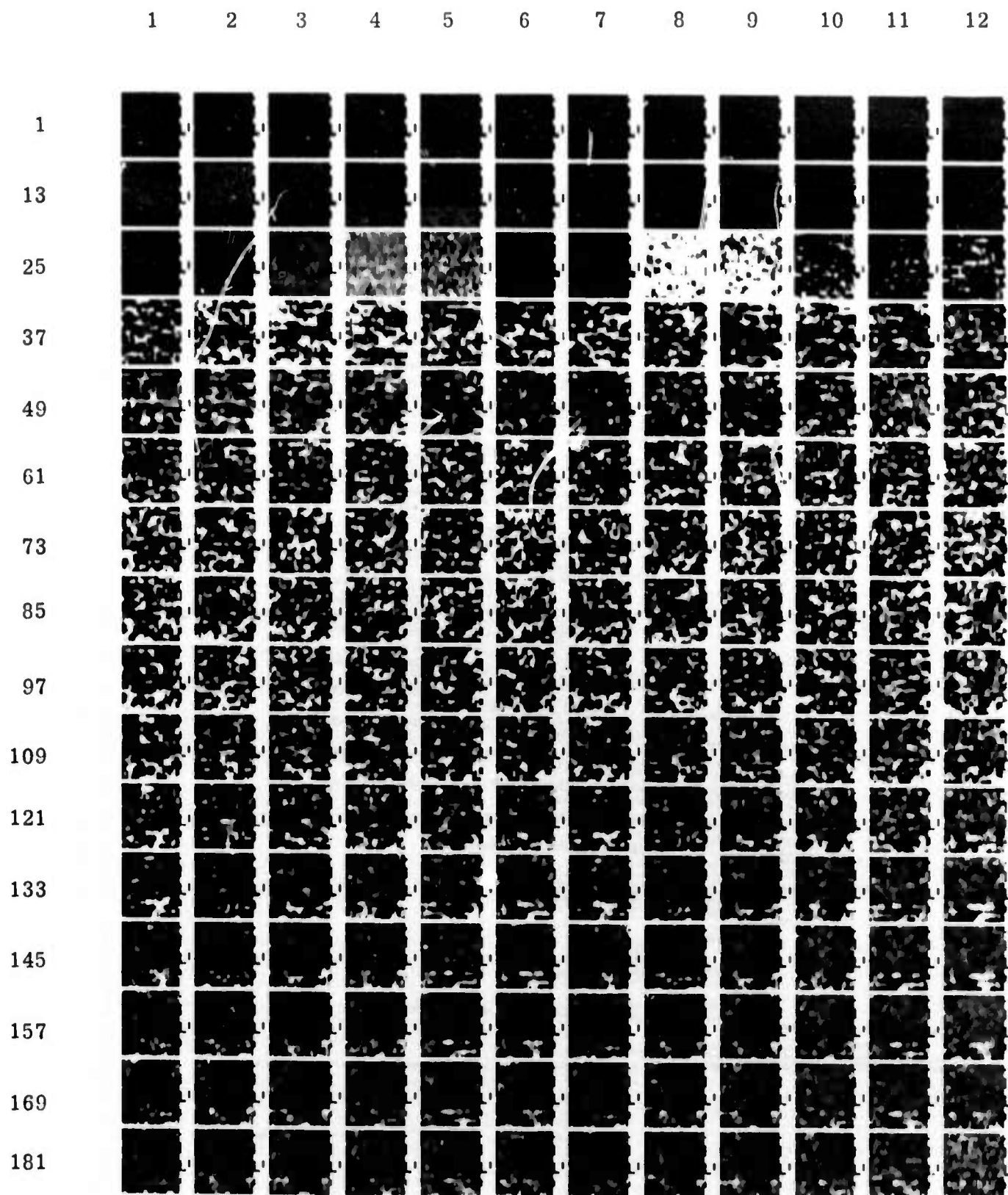


Figure 15. Movie of Frame 16 Aligned by First Peak and Highpass Filtered. (Movie frames read left to right starting at the top row. Frame interval is .014 milliseconds.)

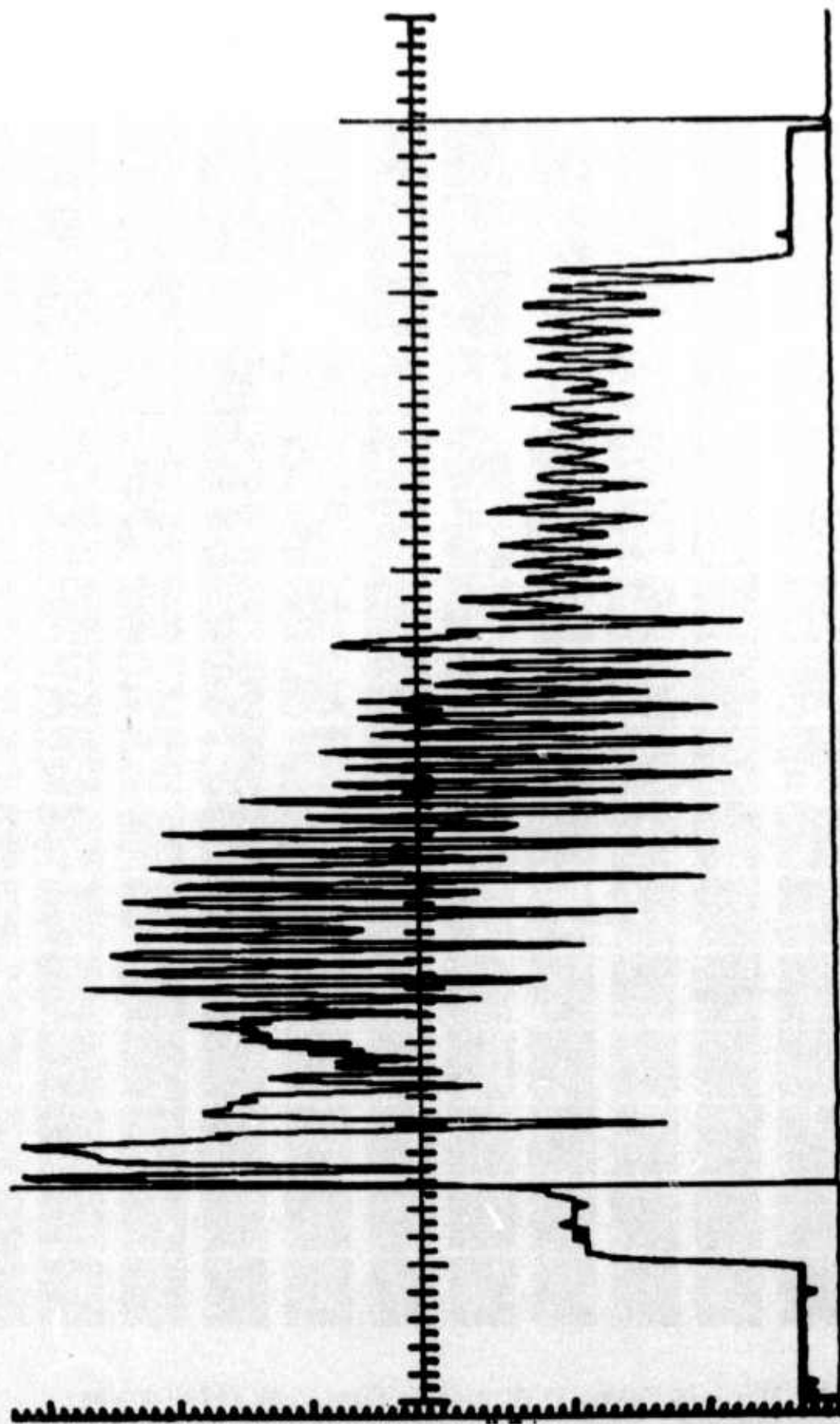


Figure 16. Figures 16-18 Show a Digitized Waveform and the Result of Bandpass Filtering It at 12 kHz and 6 kHz.

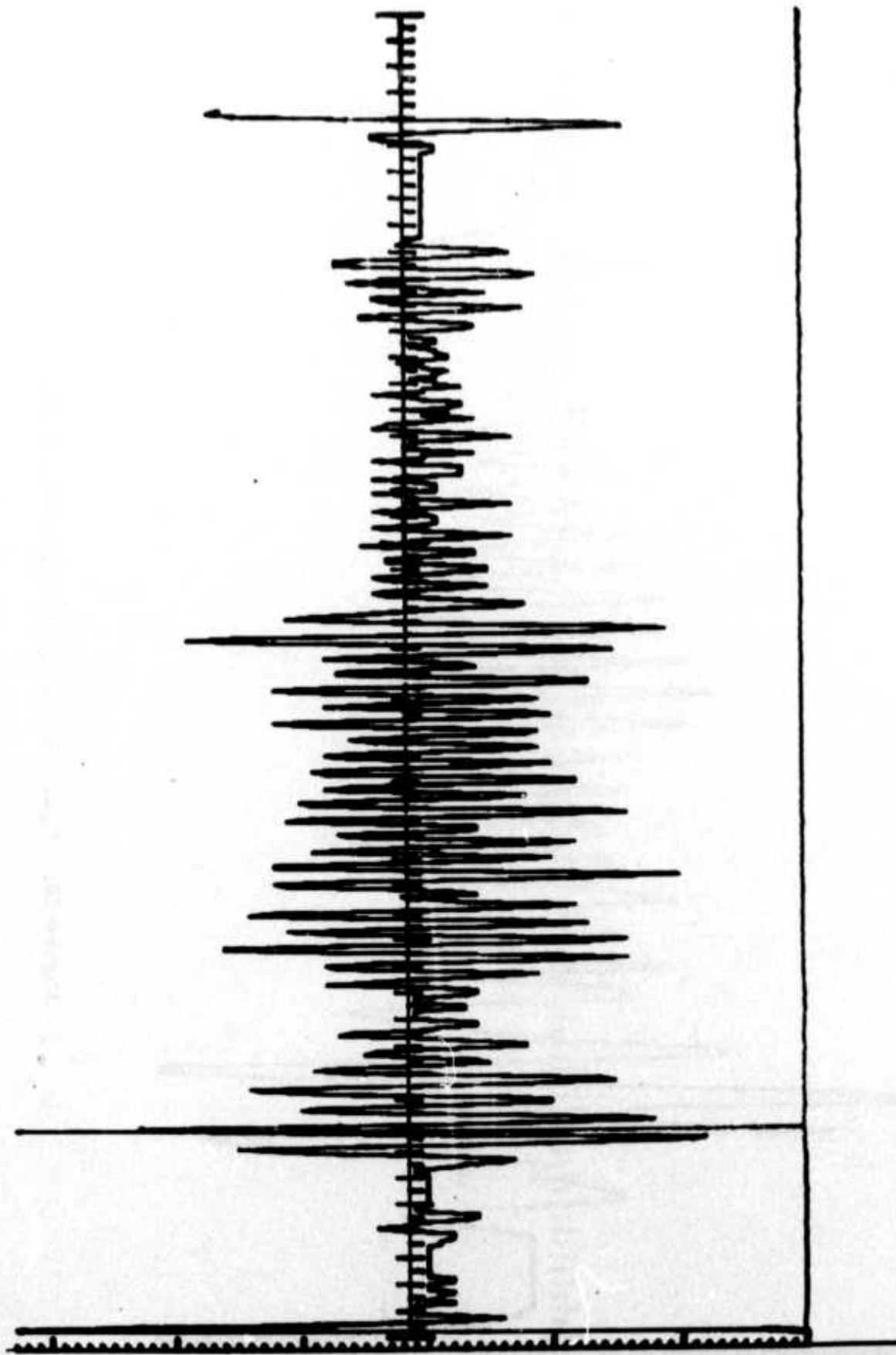


Figure 17. Figure 16 Bandpass Filtered at 12 kHz.

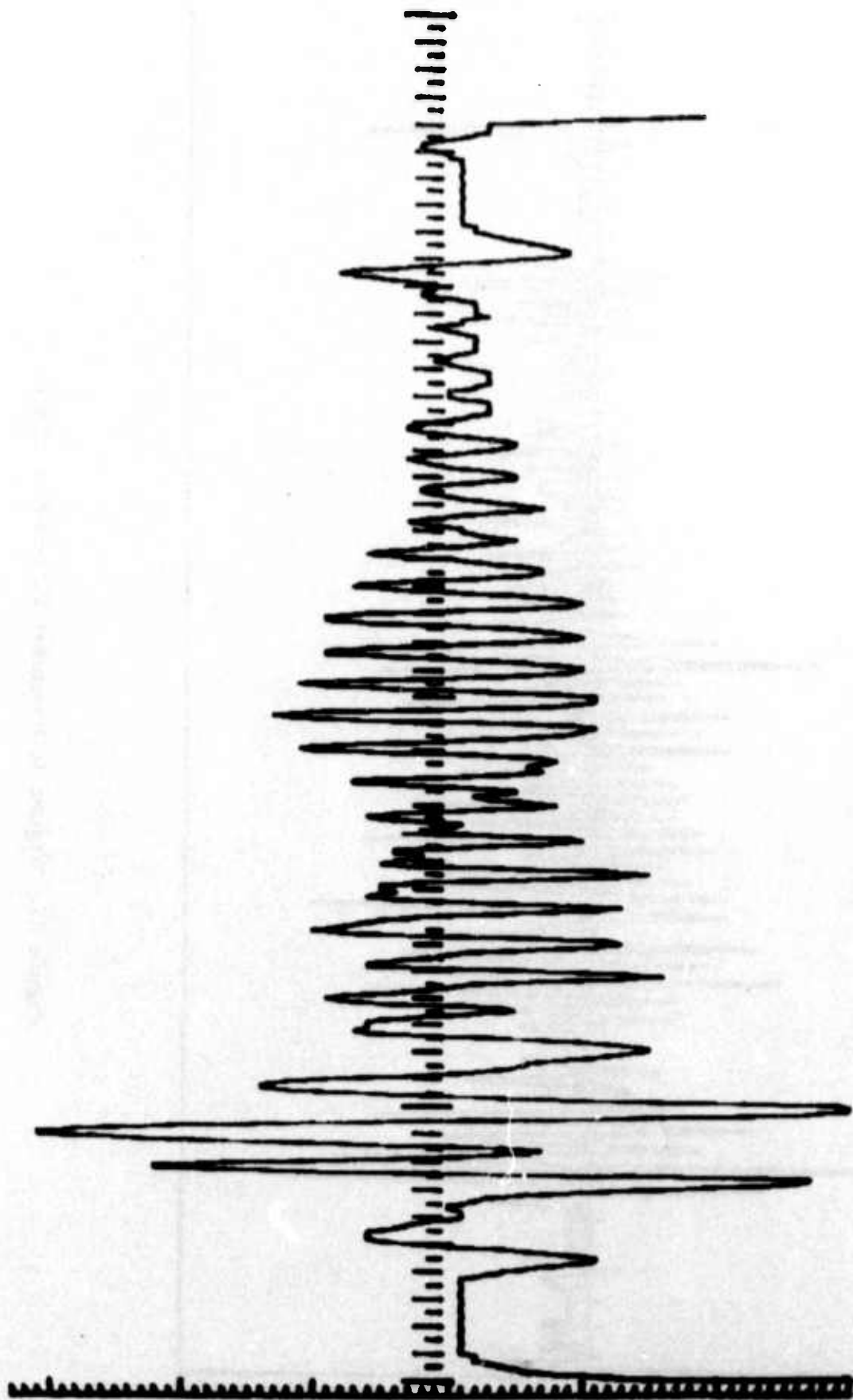


Figure 18. Figure 16 Bandpass Filtered at 6 kHz.

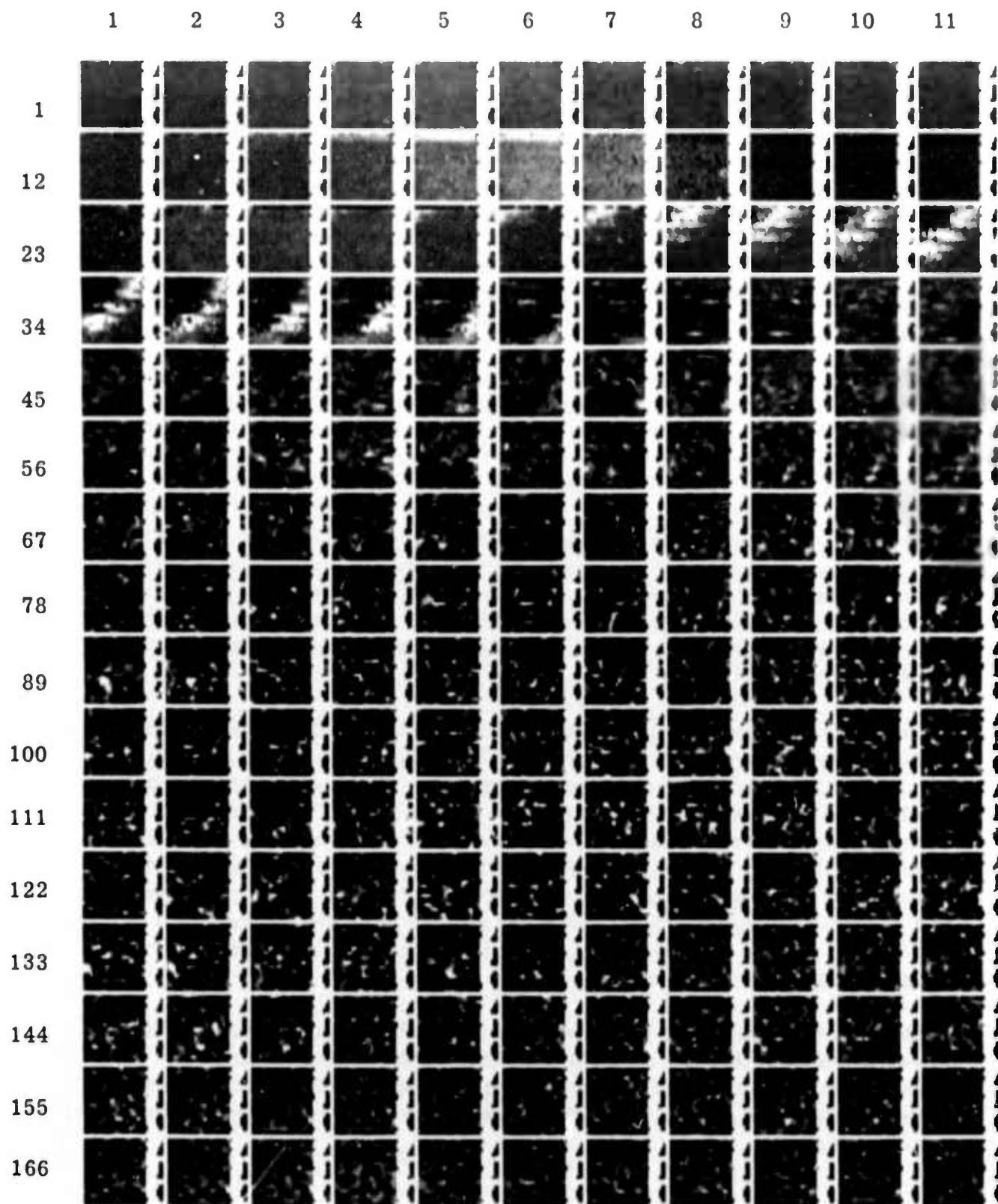


Figure 19. Movie of Frame 16 Showing Direct and Reflected Waves.
(Movie frames read left to right starting at the top row.
Frame interval is .014 milliseconds.)

photograph with a .1 mm aperture, each band (15 lines) produced 28 samples. Since there were 15 bands, the natural movie frame format would be 28 x 15 pixels. Because of the slight overlap between adjacent lines on the original picture, this format looked fuzzy in the horizontal direction (due to the averaging effect of the overlap), but was very sharp vertically. The net effect was that of extreme astigmatism and was very uncomfortable to view. To counter this, an extra pixel row was placed between each two original rows. This extra row was generated by averaging the intensities of the two rows. This makes the frame equally fuzzy in both directions and thus easier to look at.

The effect of using internal triggering and the alignment done during editing is that the peak of the direct p-wave appears simultaneously at all points of frame 21. (For this part of the discussion the term "frame" will mean a single frame of the movie.) In frames 25 through 42 there is a very clear wave propagating from the upper left to the lower right corner. Because of this wave's intensity and direction, it must be the direct s-wave. (Computer simulations verify this conclusion.) Finally, in row 5 there is a faint wave, making a 60 degree angle with the horizontal, propagating from left to right. It appears first in frame 46 and can be followed to frame 56. A number of considerations lead to the conclusion that this is an s-wave reflected from the fault. The following arguments are given to affirm this conclusion.

We can easily eliminate reflections from the surface by the direction of travel. The upper left corner of each frame corresponds roughly to the location of the equivalent point sound source. The rock surface is beyond the lower right corner. Figure 20 illustrates this. The upper left corner of each frame corresponds to source position 1 and receiver position 1. In the figure, this is at the midpoint of the line connecting source 1 to receiver 1. The shaded area is the equivalent image area corresponding to the frames, and the equivalent point source is at the intersection of the two lines. Thus a surface reflection would appear to propagate in the opposite direction to a direct wave.

In the experimental area the only other large discontinuity was the fault. It was approximately 4 feet from the plane of the holes. Using $v_p \cong 16$ ft/msec and $v_s \cong 10$ ft/msec and assuming the fault plane and the hole plane to be parallel, we get the following approximate arrival times for reflected p- and s-waves:

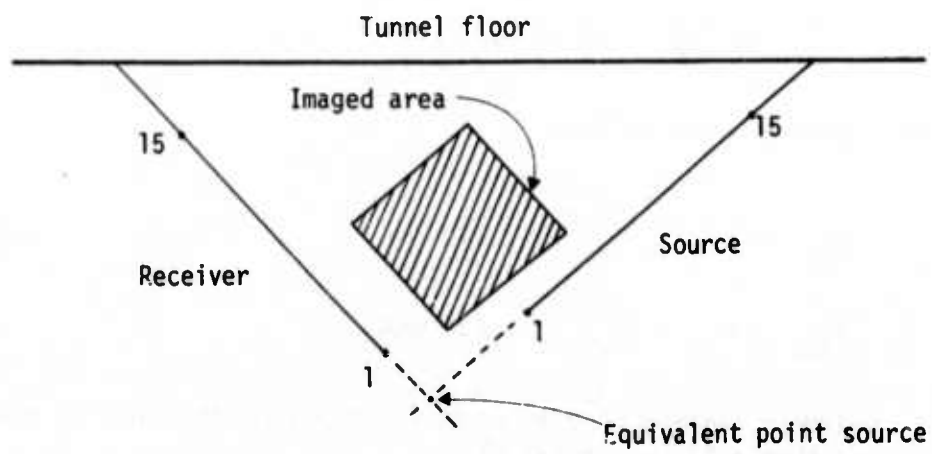


Figure 20. Image Area and Point Source Relative to Test Holes.

$$T_{rp} \cong \frac{8}{16} = .5 \text{ ms}$$

$$T_{rs} \cong \frac{8}{10} = .8 \text{ ms}$$

Because of the triggering and alignment, these must be referenced to the direct p-wave arrival time. The distance between source 1 and receiver 1 is approximately 3.3 feet (determined from measurements made during the experiments). Thus

$$T_{dp}^{1,1} \cong \frac{3.3}{16} = .206 \text{ ms}$$

The time-after-trigger is thus

$$t_{rp} = T_{rp} - T_{dp}^{1,1} = .294 \text{ ms}$$

$$t_{rs} = T_{rs} - T_{dp}^{1,1} = .594 \text{ ms}$$

The time between frames in Figure 19 is .014 ms; thus the number of frames from frame 21 to arrival is

$$n_{rp} = \frac{.294}{.014} = 21$$

$$n_{rs} = \frac{.594}{.014} = 42$$

This calculation is for arrival at the equivalent source position which does not appear on the frames. For the general case, let

d_{ij} = distance between source i and receiver j ,

p = distance from holes to fault,

r_{ij} = reflected path length from i to j

then using the previous notation and using superscripts to denote the source-receiver pair:

$$r_{ij} = \sqrt{d_{ij}^2 + 4p^2} \quad 1)$$

$$T_{dp}^{ij} = \frac{d_{ij}}{v_p}, \quad T_{rx}^{ij} = \frac{r_{ij}}{v_x} \quad (x = p \text{ or } s) \quad 2)$$

$$t_{rx}^{ij} = T_{rx}^{ij} - T_{dp}^{ij} \quad 3)$$

$$n_{rx}^{ij} = \frac{t_{rx}^{ij}}{.014} \quad 4)$$

The approximate distance from source 15 to receiver 15 is 7.9 feet, thus we find

i	j	d_{ij}	r_{ij}	T_{dp}^{ij}	t_{rp}	n_{rp}	t_{rs}	n_{rs}
1	1	3.3	8.1	.206	.302	21.6	.604	43.1
15	15	7.9	11.2	.494	.206	14.7	.636	45.3

This says that the reflected p-wave arrives first at 15, 15 and moves toward 1, 1--opposite to the observed wave in Figure 19. The reflected s-wave moves in the correct direction, but it arrives too late and moves too fast to agree with Figure 19.

The critical assumptions for this example are parallelism of fault and hole planes and the values for v_p and v_s . In fact, the planes are not parallel, and the above example gives reason to suspect that the angle is significant. The nominal value for v_p was roughly checked during the experiments by timing first arrivals with an oscilloscope. The values obtained were generally in the 15 - 17 ft/ms range. The shear velocity could not be checked so easily because of resonances.

To use the actual hole and fault geometry and test a range of v_s values requires a computer. But there is a way around this. Equations 1) - 4) hold for each ij pair, but the value of the perpendicular distance p is different for each ij pair. We can easily calculate this and make comparisons with the fault measurements.

Assume the observed wave in frames 46 - 56 is an s-wave (i.e., $x = s$ in 2) - 4)). Then from 2) and 3) (dropping superscripts)

$$\frac{r}{d} = \frac{r/v_s}{d/v_s} = \frac{T_{rs}}{T_{ds}} = \frac{t_{rs} + T_{dp}}{t_{ds} + T_{dp}} = K \quad 5)$$

and from 1)

$$\frac{r}{d} = \sqrt{1 + \left(\frac{2p}{d}\right)^2}$$

thus

$$p = \frac{d}{2} \sqrt{K^2 - 1} \quad 6)$$

The values of d_{ij} are known quite accurately, and K can be found from the observed frames and the assumed value of v_p . Thus:

$$K = \frac{.014 n_{rs} + d/v_p}{.014 n_{ds} + d/v_p} \quad 7)$$

We then have $n_{rs}^{11} = 46 - 21 = 25$, $n_{ds}^{11} = 25 - 21 = 4$, etc.

i	j	n_{rs}	n_{ds}	d	K	$\sqrt{K^2 - 1}$	p
1	1	25	4	3.3	2.12	1.87	3.08
15	15	35	21	7.9	1.25	.75	2.96

By a graphical construction from the measured fault and hole geometry, the values of $p_{11} \cong 2.8$ feet and $p_{15, 15} \cong 3.8$ feet are found. If we take into consideration the fact that the rock near the fault is filled with fractures that can open and become reflectors near the surface, then these two sets of distances agree very well.

If we assume the wave in row 5 is a reflected pressure wave, then we know n_{rp} from Figure 19 and can calculate

$$r = v_p T_{rp} = v_p (.014 n_{rp} + \frac{d}{v_p}) \quad 8)$$

and

$$p = \frac{1}{2} \sqrt{r^2 - d^2} \quad 9)$$

Carrying out this calculation yields

$$p_{11} = 4.2 \text{ ft. and } p_{15,15} = 6.8 \text{ ft.}$$

These are a much worse approximation to the "measured" values.

Based on these two tests (direction of travel and perpendicular distance), the obvious choice for the identity of the wave in row 5 of Figure 19 is a shear wave.

Frame 16 was one of five frames that were digitized, frames 3, 6, 13, and 19 being the other four. The reason for selecting these five frames was that they represent all 4 hole pairs and that the picture problems (alignment, intensity, etc.) were minimal (or at least solvable) for these five frames. Figures 21 and 22 show the raw data for frames 13 and 19, respectively. Frame 19 (hole pair 3) shows some structures that are probably due to propagating waves. However, it was not possible to align this frame, and the results from processing the unaligned data were negative. Frame 13 was produced while the external synch was working. This frame was easy to align, and it was processed with the same 5 kHz - 7.5 kHz bandpass filter that produced Figure 19. Figure 23 shows the resulting movie. This appears to show the synch pulse in row 3, but the rest of the picture is chaos. An explanation for the failure to reveal the direct waves was not pursued, but a computer program malfunction is suspected. In any event, it is doubtful that the reflected wave would be visible in this frame since its amplitude was so low for hole pair 1.

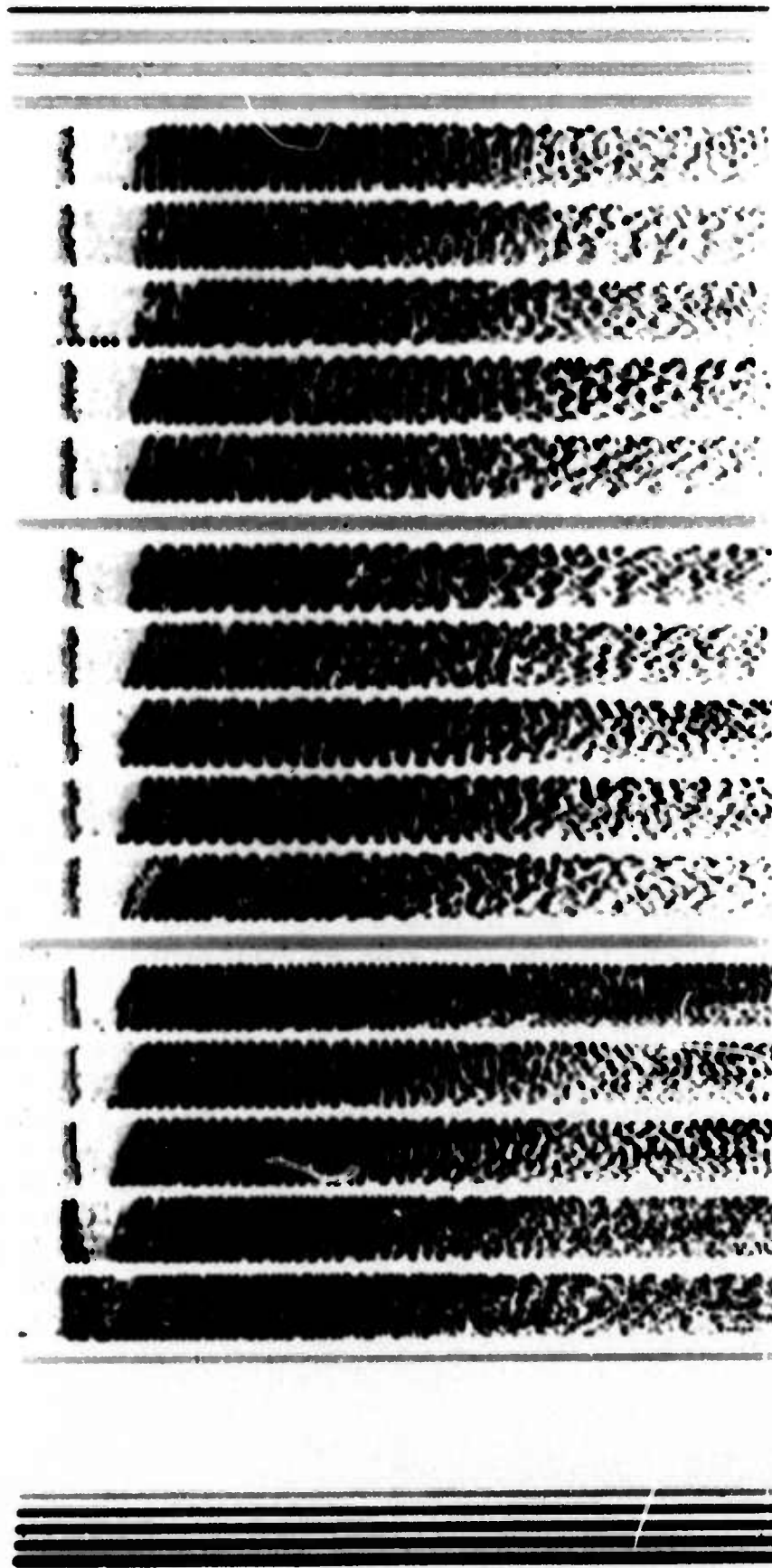


Figure 21. Frame 13: Data Recording from Hole Pair 4.

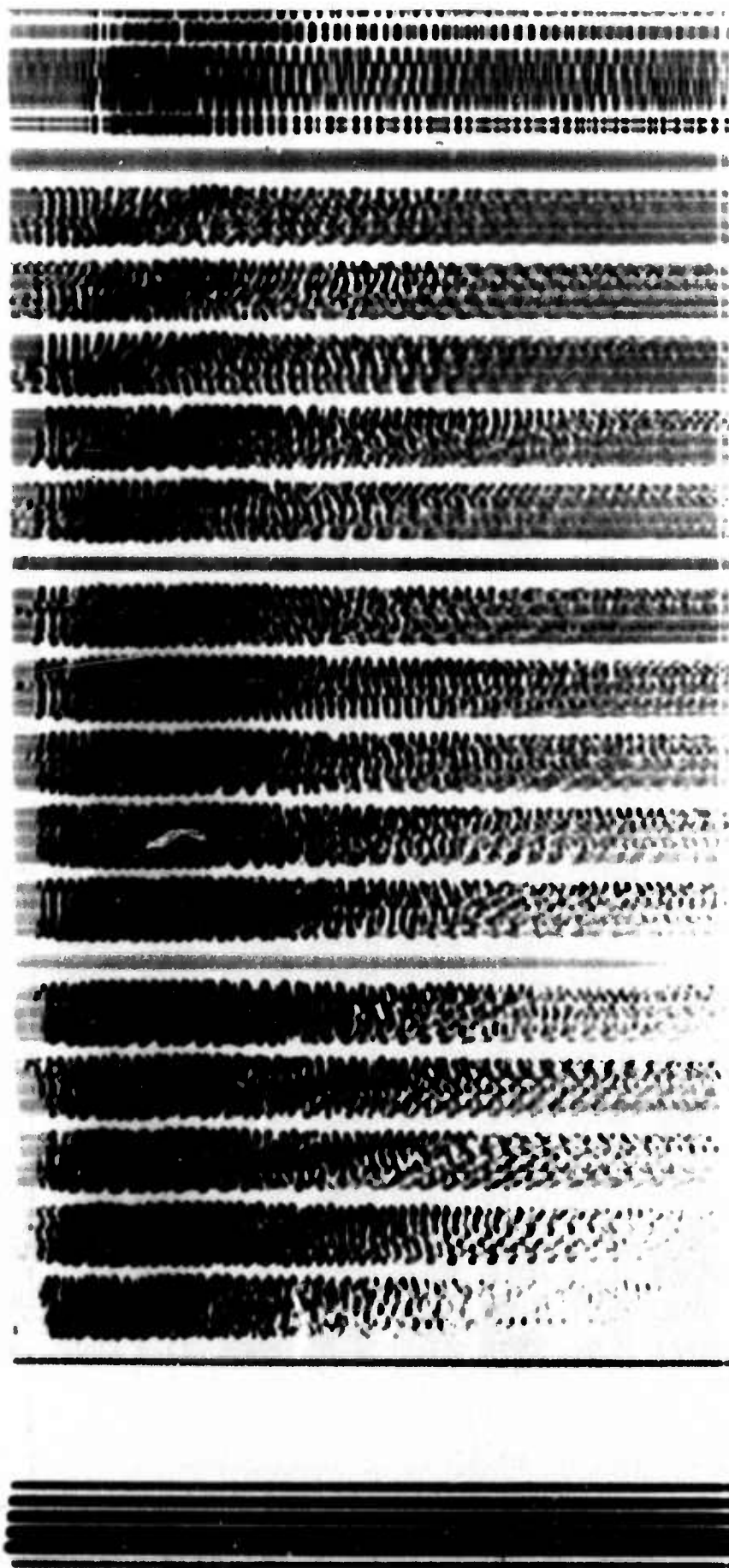


Figure 22. Frame 19: Data Recording from Hole Pair 3.

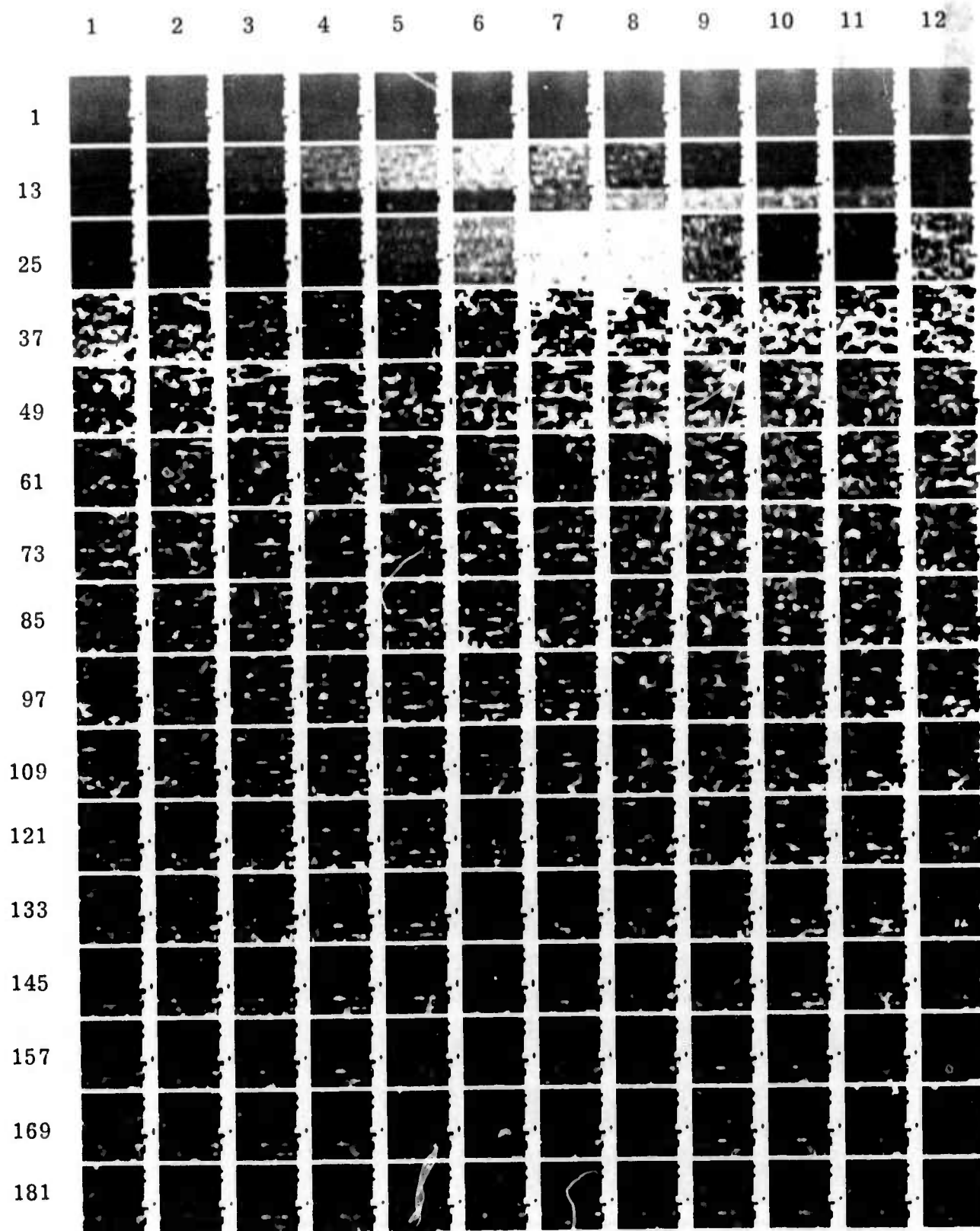


Figure 23. Movie of Frame 13. (Movie frames read left to right starting at the top row. Frame interval is .014 milliseconds.)

B. Incidental Experience

During the data collection period in the mine we encountered numerous problems caused by the underground environment. Most of these were quickly identified and solved. These have been discussed earlier. However, during November 17 - 20, the equipment was plagued by "self-triggering" due to high amplitude pulses being picked up by the accelerometer. Experimental problems do not normally merit discussion as results. The reason these are mentioned here is that these experiments involved a frequency range not normally studied, and there are correlated physical activities that may be of interest to other investigators. The observations made were not made as a controlled experiment, and conditions limited the time spent studying causes and explanations; thus the hypotheses are stated in the most tentative way.

During November 17, 19, 20, and 21 (November 18 was a day off), the transient recorder was operated with the internal trigger. Previous to this time the external trigger mode was used, but this started to cause problems that interfered with the data recording so the other mode was used. Thus, if the pulses had been happening earlier, they would not have been noticed. During November 17 and 19, there were time periods 20 to 50 minutes long when data collection could not be done because these pulses would trigger the transient recorder as soon as it was reset. During these times there were two kinds of pulses being detected. One was an exponentially decaying sinusoid with time constant of $1/2$ ms to 1 ms, peak amplitude of 2 mv to 10 mv, and frequencies of $3-1/4$ kHz, $6-1/2$ kHz, and 13 kHz. The other kind was a non-coherent pulse train, lasting up to 50 ms, having peak amplitudes (for the individual pulses) of 2 mv to more than 100 mv. The envelopes of the individual pulses were generally quite smooth with the leading edge increasing somewhat more rapidly than the trailing edge decreased. Figure 24 is a rough sketch of this kind of envelope. Also in the second class were pulse trains and individual pulses with no clearly defined envelope. The exponentially decaying pulses were well explained on November 20 as being due to slippage of the rubber parts that held and supported the accelerometer mounting. This slippage was eliminated by lubricating the entire accelerometer assembly with silicon grease. The $6-1/2$ kHz frequency was similarly identified as the resonant frequency of the accelerometer as it was mounted, the other frequencies being harmonics and sub-harmonics of this frequency.

An equipment cause for the other class of pulses was not discovered, and they were not seen after November 19. The correlated activity in the mine

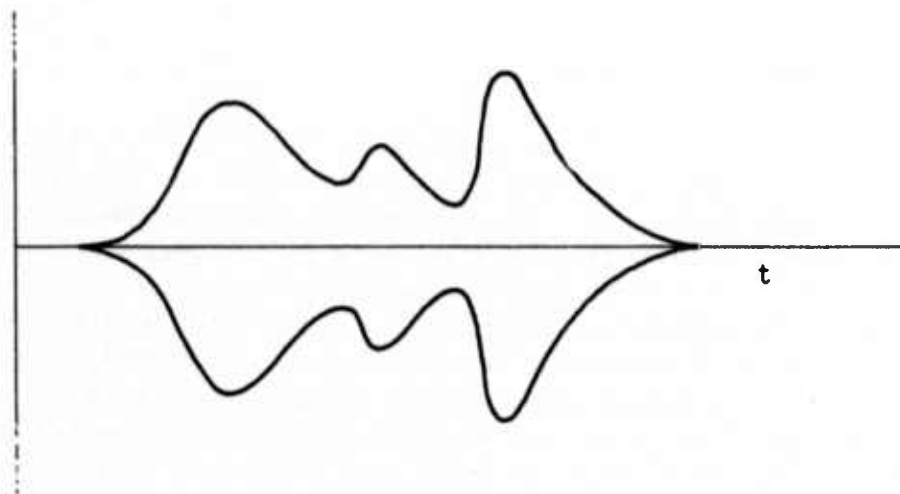


Figure 24. Sketch of Non-coherent Pulse Train Envelope.

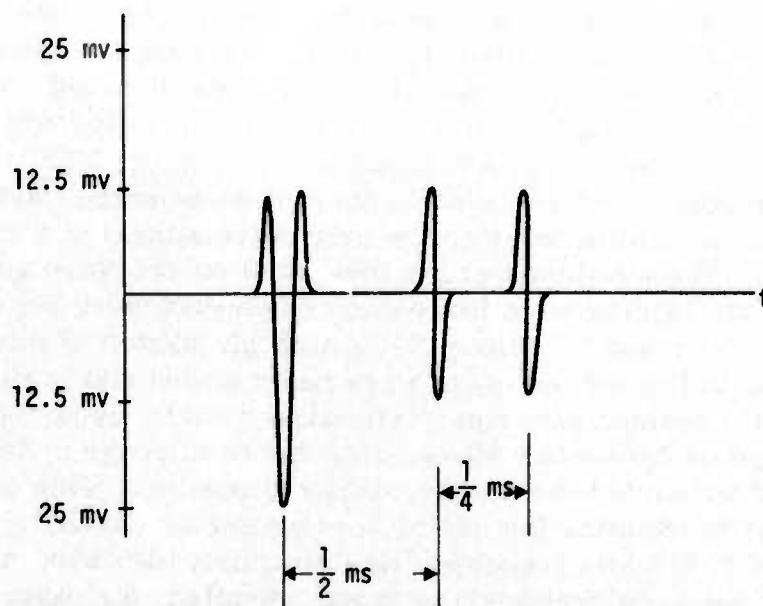


Figure 25. Pulse Shape Associated with Hydraulic Power Pack Starting.

that makes this of interest is that during November 17, 18, and 19, there was a great deal of rock dribbling from the back in the experimental area. (The experimental area was quiet; thus this activity could be heard, whereas it would probably not be noticed in a working area unless someone were hit.) This rock dribbling was very rare at other times. Also during this time miners reported a lot of rock noise (cracking, popping) in the mine areas where pillar robbing was going on and near the large faults. Also there were at least four large rock falls and cave-ins in the working areas of the mine during this period. (The last one happened during the night of November 19.) Finally, in at least one area, mining in a drift was stopped because of large cracks appearing in the floor and back, rocks popping from the ribs, etc. All of this geological and seismic activity ceased after the night of November 19 as did the problem with the self-triggering. It is a tempting hypothesis that the gross physical activity in the mine and the microseismic activity observed by our equipment were related, particularly since the signal observed in the 5 kHz - 20 kHz range would only travel short distances and thus would reflect local conditions. This might provide a means of predicting cave-ins and rock falls and for monitoring pillar robbing areas.

Another kind of pulse activity was encountered on November 20. During this day, technicians were repairing and testing a hydraulic power pack in an area about 180 feet from our experimental site. Each time this device was started, and the pumps pressurized the hydraulic system, our transient recorder would trigger and record a pulse like the one sketched in Figure 25.

Over 20 of these events were observed. We could hear the motors being started and a pulse of the kind shown was detected each time. The power pack was being operated from a different transformer than we were using so the probability is low that this could be an electrical transient. We also intentionally disconnected the accelerometer from the recorder input for two starts and did not receive the pulse.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

The main conclusion from this study is that this method of acoustic imaging can detect and locate hard rock faults using equipment and procedures compatible with the commercial mining environment. The fault's range and strike angle can be found quite easily using equation 6) of Section 4A. No conclusions can be made about the maximum range (image plane to fault) for the method, but we feel that the lack of positive results for the 8 foot to 16 foot ranges was due to data processing problems and not due to lack of signal reflection from the fault. Individual waveforms recorded during the 16 foot range experiments show pulse arrivals at the times expected for the reflected wave, and with proper alignment and filtering these presumably would be observable in the movie format. (The failure to detect the direct wave in the longer range movies gives additional support to concluding that data processing problems were the limiting factor.) The received signal to noise ratio will be the ultimate limit on the detection range. Our experience indicates that the environmental noise is very low at the frequencies used, and the major noise sources are in the equipment (electrical noise and mechanical resonance). These noise sources can be minimized by the equipment design and thus extend the detection range. The transmitted signal power can also be increased quite easily by increasing the voltage discharged across the spark gap. Doubling this voltage will increase the signal power approximately four times and thus double the range. During this study the discharge voltage used was from 1.4 KV to 2.4 KV, and the maximum voltage setting for the power source was 3 KV. These values were determined by the particular equipment design selected and can be increased through different equipment design.

This study allows a number of conclusions about the data collection and processing. Signal phase is the important signal feature in this method, and signal amplitude contains very little information. Thus high gains that cause signal clipping and film saturation can be used to enhance the signal without losing information. The hole depth, arrangement, and accuracy were sufficient to perform fault detection. In fact, both simulation and analysis of the experimental data indicate that these parameters can be varied widely without affecting the fault detection results. The main constraint on the hole placement in a working mine would be to place them as close to the working face as possible to allow best detection of faults that dip away from the image plane. Finally, it appears that fewer source and receiver positions could be used and still produce a good movie of the reflected wave. A 10 x 10 image array would not seriously degrade the image quality, but it would about halve the data collection time and effort relative to the 15 x 15 array used in this study.

Numerous suggestions are made in Sections I - IV. These are briefly summarized below:

Signal Conditioning

- Use a narrow bandpass filter on the transducer output during the data collection. The band should be selected to match the rock resonant frequency and reject system resonances.
- The transducer output can be highly amplified without losing the useful information. Signal clipping and display saturation are acceptable, but saturation of the electronics should be avoided because of possible phase distortion. A logarithmic amplifier would meet the requirements very well.

Data Recording

- Film proved quite adequate for recording the received signals, and it is hard to conceive of any other recording method with comparable cost effectiveness.
- A 35 mm camera with automatic step film advance would solve a number of the problems encountered during this effort, notably the "herring bone" caused by unequal film advance and the problems of keeping track of film position during manual operations. Also, 35 mm film will provide a long enough signal trace for recording frequencies in the 5 kHz range.
- The transient recorder reset, the film exposure and film advance should all be caused by a single operator action, such as a single button push.
- The format for recording data on film needs further study. The calibration lines used in this effort are unnecessary. The overlap of adjacent lines on the film caused some problems for the computer processing and the resulting astigmatic effect (horizontally blurred and vertically sharp movie frames) would make viewing uncomfortable with a fiber optic viewer. Separation between adjacent lines could simplify the computer processing.
- Whether external or internal synch is better for viewing was not settled. The external synch would give better time resolution, but it would also require greater film width for the same frequency resolution and would cause images to move across the movie frames more rapidly. Some simple simulations could resolve this question.
- The oscilloscope used to monitor the received signal was extremely useful during these experiments and is recommended as part of the equipment configuration.

Mechanical

- It is recommended that a mechanical mounting, attached to a rigid rod, be used to hold the accelerometer/transducer in place. The pressure hose and flexible tubing arrangement used in this study was the source of many problems including alignment and positioning difficulties, hose rupture and extraneous pulses caused by slippage of the flexible parts.
- The mechanical resonances of the transducer assembly should be studied and compensated to eliminate ringing that interferes with observing the received signal.
- The image plane was placed approximately perpendicular to the tunnel floor in these experiments. However, in observing in front of an advancing tunnel, it may be advantageous to direct the image plane forward from the tunnel face. This could permit observing faults with dip angles that would cause reflections to be shadowed by the fracture zone around the tunnel.

Electrical

- The electrical equipment should be isolated from line fluctuations and from the spark power source. A precision power supply can provide this function.
- The problems with spark source erosion are discussed at length in the report. Some other design, maybe like an automobile spark plug, is strongly recommended.

Display

- There are many difficulties involved in using a digital computer to display the movie outputs, and the computer processing seems to be a poor alternative to the extremely simple fiber optic viewer. However, the alignment and filtering problems encountered in these experiments would have made the fiber optic viewer totally ineffective. For further developmental work, it is recommended that computerized processing be used.

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