DEVELOPMENT OF AN INTEGRATED MONITORING SYSTEM FOR EVALUATING ROOF STABILITY

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Abstract

Cooperative research between U.S. Bureau of Mines and Colorado School of Mines investigators has resulted in the development of a seismic system to evaluate roof stability in underground mines. After considering seismic, electrical resistivity, gravity/magnetic, and electromagnetic methods, a crosshole seismic method was chosen as the best means of detecting roof stability problems in sedimentary rocks. This choice was based on (1) evaluation of degree of resolution and depth of penetration for every geophysical technique considered and (2) an analysis of failure mechanisms in U.S. mines where significant deformation and changes in rock mass properties have occurred over time.

After a review of geologic, geophysical, and rock mechanics data from four mines, a field site was selected near Green River, WY. An instrumentation plan was developed for monitoring strata movement, pillar stresses, and changes in material properties during both development and retreat mining. This program was designed to complement seismic data with a precise picture of strata movement, fracturing, and stress distributions. Field testing of this integrated system has been completed.

Introduction

The U.S. Bureau of Mines has supported long-term studies for detecting stability problems and improving safety in U.S. coal mines. These studies have focused either on the use of standard rock mechanics instruments or geophysical techniques. During this study, an attempt was made to use both types of techniques to monitor changes in strata deformation and material properties during the life cycle of entries.

The objective of this research was to develop integrated instrumentation techniques to enhance understanding of strata deformation and failure mechanisms during active mining and to eventually provide a means of warning against impending roof stability problems. To achieve this goal, we have developed an integrated rock mechanics instrumentation and crosshole seismic method.

For the most part, application of controlled-source geophysical techniques in the mining industry has been restricted to exploration of mineral deposits. The oil and gas industry and nuclear waste agencies have often used geophysical techniques for geological characterization. Table 1 provides an overview of mining, oil, and nuclear waste industry applications. Useful geotechnical data can be obtained during mining exploration through the utilization of selective geophysical logs (Table 2). For details of theoretical concepts and terminology, see Hearst and Nelson (1985).

Underground geophysical techniques have been used to detect faults (Dobecki and Bartel, 1981; Jackson and Taylor, 1984), sand channels (Walker, 1979), and stress-related fractures (Jung et al., 1991). Crosshole methods have been widely implemented using surface boreholes to detect fractures, cavities, and sand channels (Wong et al., 1987; McCann et al., 1986).

Review of Stability Problems

During the deposition and consolidation of geologic materials, a number of lithologic and structural defects are formed within coal measure rocks. Such defects include rider seams, coal seam interfaces, slickensided contacts and joints, sandstone channels, plant fossils, faults, joints, and bedding planes. Mechanical properties of these defects are generally the parameters that control rock mass stability (Table 3).

Stress-related stability problems are common in U.S. coal mines (Maleki et al., 1991). During the excavation of coal, stresses redistribute around entries until a state of equilibrium is reached. During this process, strata deform toward the entries either in a stable or an unstable manner.

Cutters and kinks are common forms of failure in Eastern and Midwestern coal fields; pillar squeeze and coal bumps occur in both Western and Eastern coal seams; buckling and squeeze have been reported in Eastern (Aggson, 1978), Midwestern, and Western coal fields (Maleki et al., 1991).

Selection of Prudent Monitoring Systems

The focus of this paper is on what measurement techniques are suitable for detecting roof stability problems during excavation. Both standard rock mechanics and geophysical methods are considered.

Use of total roof deformation and deformation rate are the most simple, practical measures for detecting roof stability problems (Maleki, 1988b; Maleki, 1990; Maleki and McVey, 1988). These measurements rely on the ability of geologic material to deform up to several inches in an elastic manner, depending on lithologic composition. Beyond this limit, rates of movement accelerate, indicating the initiation of failure, loss of support effectiveness, etc. (Maleki, 1988a). These measurements can provide an assessment of instability at the point the measurements were taken. However, there is some level of interpretation and engineering judgment required for effective use of these measurements in ground control.

Geophysical techniques may be used for monitoring changes in elastic wave propagation through strata; to detect roof stability problems, one needs to establish critical changes (or levels) of wave velocity, frequency, and attenuation, which are indicative of the development of stability problems. One advantage of geophysical measurements is that they offer the capability of averaging wave properties over much larger volumes of rock than do deformation measurements.

Table 4 presents a summary of geophysical techniques suitable for roof stability assessment; this selection was based on degree of resolution and depth of penetration. Seismic and borehole electrical techniques are more suitable than others (gravity, magnetic, and ground-penetrating radar). With a high-resolution seismic survey, one can examine the development of fractures in a mine roof over time and have a depth of penetration from 10 to more than 50 feet, depending on the source energy, for most coal-measure rocks. Electromagnetic methods and ground-penetrating radar, on the other hand, have a limited depth of penetration, particularly in shales (Snodgrass, 1991).

Both seismic and electrical resistivity techniques are sensitive to either changes in groundwater quantity and/or composition. For this reason, a site was selected where changes in groundwater conditions were insignificant during the monitoring period. To study roof failure processes, there is a need to supplement seismic data with rock mechanics information. In this study, we have integrated crosshole seismic and deformation measurements to assess roof stability. Other measurements and underground observations have also been used to study complex interactions among roof, pillar, and floor.

Development of a Crosshole Seismic System

Overall System: The data acquisition system used in this study was assembled from off-the-shelf components. A computer-based, eight-channel system with differential inputs and programmable gains capable of acquiring 150,000 samples a second was selected. The data acquisition system is composed of a computer with an analog-to-digital (A/D) board, a source device, a setting device, amplifiers, filters, and a trigger unit.

The main component of the system is a computer and an A/D board. The computer is based on the 32-bit 80386 microprocessor, which will be upgraded to a 80486 microprocessor. The computer has a dual purpose: It is part of the field data acquisition system, and it serves as a graphics and computing machine. The A/D board is a DT2821 system from Data Translation, Inc. (Note: Reference to specific equipment or trade names does not imply endorsement by the Bureau of Mines.) It has eight differential input channels and programmable gains (1, 2, 4, or 8). The board is capable of acquiring 150,000 samples a second for eight channels.

The software applications developed for this study permit the seismic signal to be sampled in any combination of channels. The software also has the capability of performing limited signal data processing in the field, which enables continuous monitoring of the signal and fine-tuning field procedures. Data are recorded on a floppy diskette and on a hard disk.

Charge amplifiers are used to convert charge inputs to voltage outputs and to amplify the signal up to 100 times. The amplifiers are designed for use with piezoelectric transducers (accelerometers). Also, to remove high-frequency background noise, active low-pass filters were installed between the amplifiers and the A/D board. The cutoff frequency of these filters can be set by dip switches.

Source Devices: Two kinds of source were tested; one was a seismic detonating cap and the other was an impact unit. The cap was mounted on a 2-in-diam bronze bar and used in a 2.5-in borehole. During the testing, the cap created airwaves in near offsets while it generated weak signals in far offsets. Better signals could have been achieved by stemming the cap into the borehole, but this would have complicated use of the borehole for subsequent measurements; thus, caps were not used in this study.

The impact unit consisted of a point resin-anchored rock bolt, a 5-ft-long steel rod, and a 16-lb cylindrical steel mass (Figure 1). The steel rod was attached to the point resin-anchored bolts at the time of measurement. These bolts were anchored at 1.5, 3, 4.5, 6, 7.5, and 9 feet into the roof in a semi-circular pattern. The steel mass had a hole along its axis, permitting it to slide vertically along the rod as it struck a plate. The steel mass was free dropped from a 4-ft distance to create a consistent energy source. A steel plate at the end of the rod stopped the sliding mass during operation. The surfaces of the plate and the mass were machined to give consistent, repeatable impacts. The solid contact between the mass and the plate allowed the A/D board to be triggered at the same time energy was introduced into the rock. This source was designed to minimize error caused by triggering inconsistencies.

This source performed satisfactorily during the initial testing for picking of the first arrival time; Figure 2 presents a waveform trace for sources anchored 1.5, 3, 4.5, 6, 7.5, and 9 feet into the roof. In time, however, this source created weak signals in far offsets as a result of significant strata fracturing, which caused excessive attenuation.

Borehole Setting Devices: Two accelerometer borehole setting devices were developed and tested in this study. Each setting device has three accelerometers (receivers) at 1-ft spacings. These accelerometers are high-performance piezoelectric devices with a flat frequency response in the range of 1 to 6,000 Hz. They respond to motion in one direction and have a low transverse sensitivity. The two devices perform in a similar fashion by using air cylinders to push a contact member against the borehole wall. One device, designed by the Colorado School of Mines (CSM), has a point contact, while the other one, developed by the Bureau, has an areal contact, as shown in Figure 3.

Table 5 and Figure 4 compare the maximum amplitude and dominant frequency of traces from the two devices. The CSM device is better at measuring amplitude, while the Bureau's device is superior at measuring frequency.

This setting device is suitable for use under a variety of conditions in both coal and hard rocks; the device needs minor modifications for use in wet boreholes.

Filters and Trigger Boxes: To remove high-frequency components from the data, a battery-powered, eight-channel, programmable, low-pass filter was designed and fabricated by the Bureau. This filter was installed to condition the signal prior to its entering the A/D board. Dip switch settings in the filter box set the cutoff frequency between 1 and 25 kHz. Programming information is shown in Figure 5. A cutoff frequency of 3 kHz was used in this study.

Figure 6 presents the circuit for the battery-powered trigger box fabricated by the Bureau for this study. The trigger circuit produces a 2-microsecond, 5-V pulse coincident with the source signal, which starts the acquisition of data so that wave travel time can be determined. Minimum time interval for successive triggers was 2 seconds.

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Site Selection and Instrumentation Plan

A southwestern Wyoming trona mine was selected from four mines visited in Colorado and Wyoming (Culbertson, 1966). Site selection was based on a review of geotechnical data from these mines as well as from another 10 U.S. coal mines.

The selection criteria consisted of determining whether the site had (1) sedimentary rocks, (2) significant strata movements and fracturing, (3) insignificant ground water in a mine roof, (4) a location in the Western United States for ease of access, and (5) a high level of interest by the mining company.

Figure 7 presents a typical lithologic log, the transit time, and the electrical resistivity obtained from well logging. Roof and floor material consists of shales and marlstones, where wave velocities are in the 8,000-ft/s range. In the trona beds, wave velocities are up to 12,000 ft/s.

Figures 8 and 9 present the instrumentation plan, which consists of seismic line A-B, vibrating-wire stressmeters, rib dilation meters, floor dilation pins, and roof deformation meters (sagmeters). Mining geometry incorporated a three-entry system that uses 17- by 44-ft pillars and 18-ft-wide spans.

Pillar and floor instruments were also installed to study overall ground response, including the interaction among roof, seam, and floor. Three sagmeters were installed in the mine roof along the seismic line to measure changes in strata movement and bed separation. In addition, borehole observations were carried out to locate the position for bed separation and observe changes in roof moisture during the monitoring period. Cores were obtained twice from the roof for physical property testing.

Summary and Conclusions

A data acquisition system was developed and field tested to study the feasibility of using crosshole seismic tomography in underground mines to detect roof stability problems. Testing involved two source devices, two receiver setting devices, variable-frequency filters, and trigger boxes. These were built by Bureau and CSM project personnel. To enhance efficiency of equipment use, the system is being mounted on a truck for routine underground stability evaluations. Additional rock mechanic instruments consisted of sagmeters, stressmeters, and dilation meters. This integrated system was field-tested to monitor rock mass deformation and failure processes.

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Table 1. Applications of geophysical methods.

Method	Typical applications
Surface geophysics..............	Oil Mining exploration Geotechnical: Structure Mining cavities Ground water
Borehole geophysics.............	Oil Mining exploration Geotechnical: Lithology Structure Rock quality Hydrology
Vertical seismic profiles (VSP).. - Standard VSP - Offset VSP - Deviated well VSP - Walkaway VSP	Oil Mining exploration Geotechnical: Stratigraphy Structure Porosity
In-seam.........................	Nuclear waste Mining exploration Geotechnical: Fracture detection Sand channels Structure Stress change
Crosshole.......................	Nuclear waste Mining exploration Geotechnical: Fracture detection Cavities Sand channels Stress change

Table 2. Typical geophysical well logging in mining applications.

Method	Measurement	Application
Caliper.............	Borehole size	Weak zones, fractures
Spontaneous potential..........	Natural electrical potential	Water quality Permeability
Resistivity.........	Electrical resistivity	Permeability and porosity Bed thickness Lithology Water quality
Gamma ray...........	Natural radiation	Shale and sandstone partings
Density.............	Reflective gamma	Coal exploration
Expanded scale logs.	Density	Coal quality
Neutron-neutron.....	Reflected neutron	Water content Fracture zones
Temperature.........	Oxidation	Coal burn
Sonic...............	Velocity	Elastic properties Density

Table 3. Factors affecting stability in coal-measure rocks.

Factor	Example
Lithologic:	
1 - Unconsolidated, uncohesive rock	Carbonaceous shale Underclay
2 - Laminated, low-friction planes	Thin-bedded strata
3 - Nonuniform lithology	Channels, riders
Structural:	
1 - Unfavorable discontinuities	Joints, faults, dikes, cleats, slickensided joints
Hydrologic:	
1 - Hydrostatic pressure	Channels
2 - Chemical decomposition	Underclays
Stress-related:	
1 - Roof failure	Cutters, kinks
2 - Pillar failure	Squeezes, bumps
3 - Floor failure	Buckling, squeezing

Table 4. Evaluation of geophysical techniques suitable for stability assessment.

Method	Measured physical property	Estimate	Difficulty
Crosshole seismic.....	Longitudinal and shear wave velocities	Elastic modulus, Poisson's ratio, stress orientation, density, lithology	Velocity depends on porosity and amount of fluid
Azimuthal seismic.....	Directional velocity, shear wave splitting (Rai and Hanson, 1988)	Orientation and density of fractures	Anisotropy depends on mineralogy
Seismic refraction..	Attenuation velocity and acoustic impedance	Saturation, fractures, and lithology	Suitable for shallow mines
Electrical..	Conductivity	First bed separation	Conductivity depends on temperature, clay content, and permeability

Table 5. Averages of amplitude and frequency from two devices.

	Amplitude	Frequency, Hz
Old device....	156	735
New device....	118	787

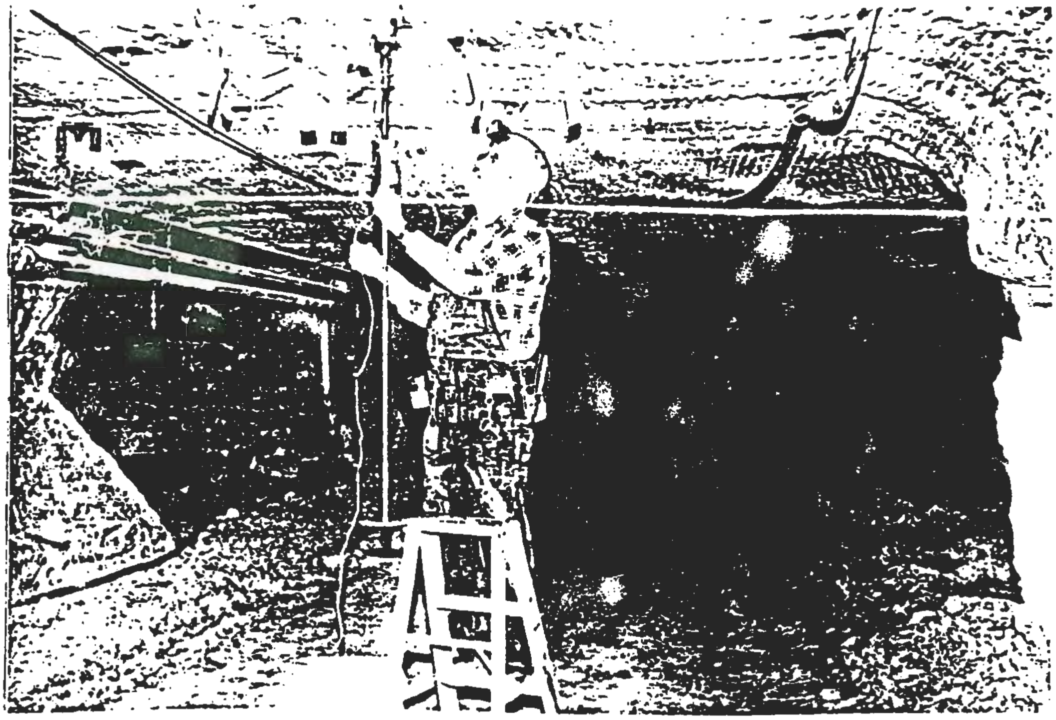


Figure 1. Application of crosshole seismic method using impact unit as energy source. The unit is attached to a point resin-anchored roof bolt.

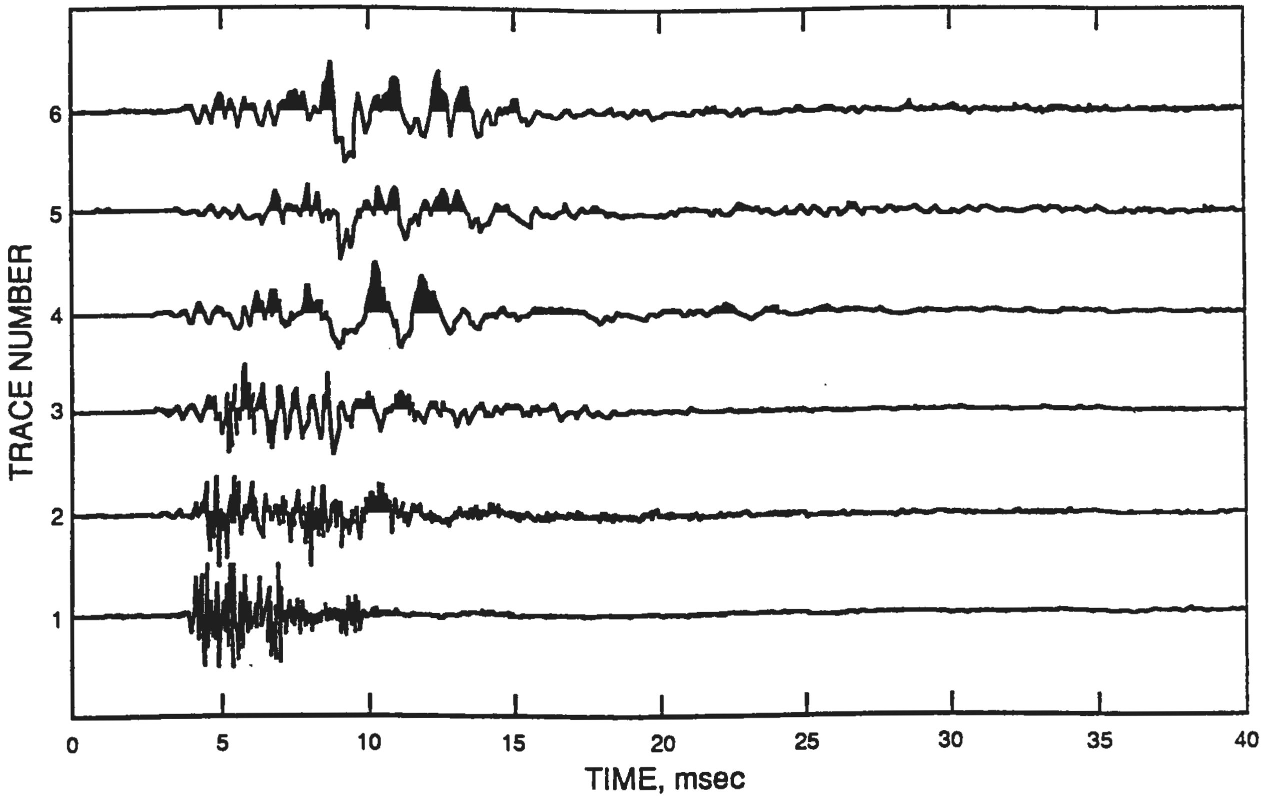


Figure 2. Waveform trace for sources 1 to 6 and a receiver at a 25-ft distance.

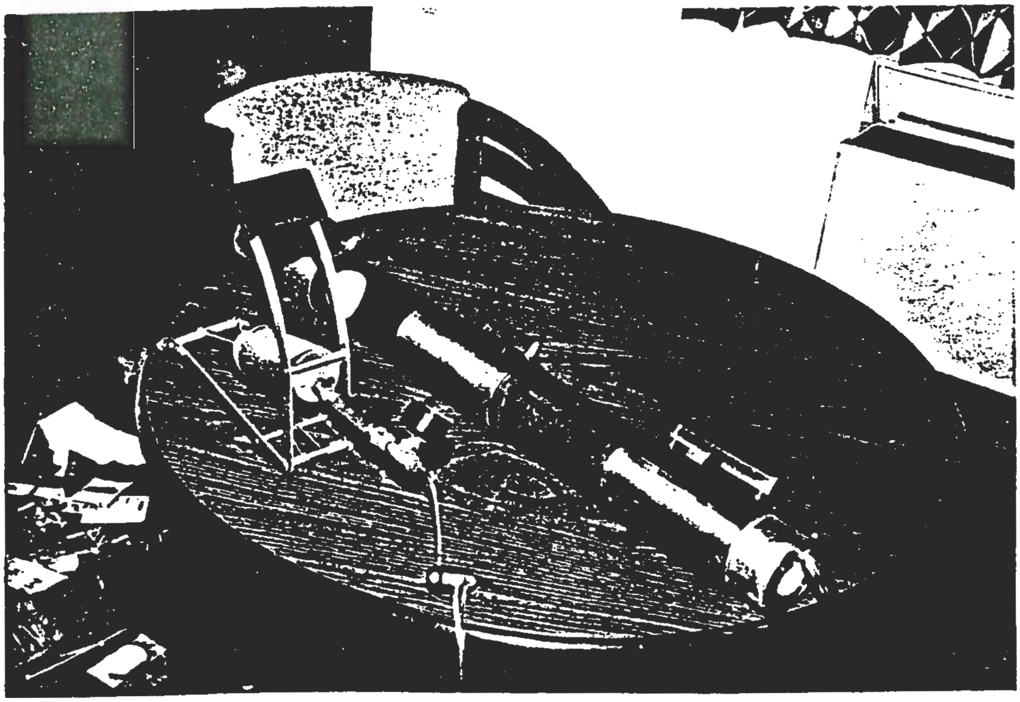


Figure 3. An accelerometer setting device for use in 3.3-in-diam borehole.

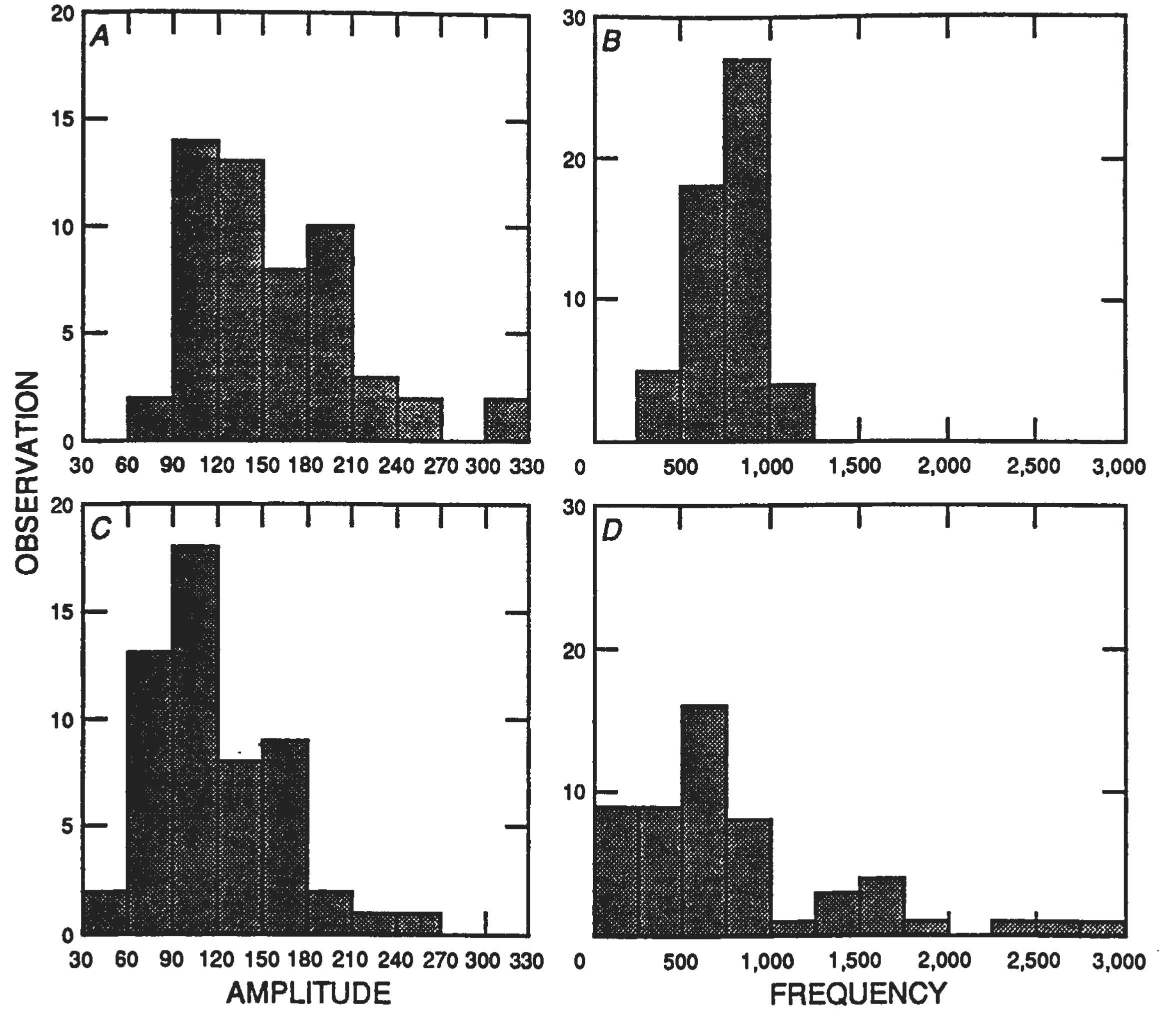


Figure 4. Histogram frequency diagram for the two setting devices. A-B, CSM device; C-D, Bureau device.

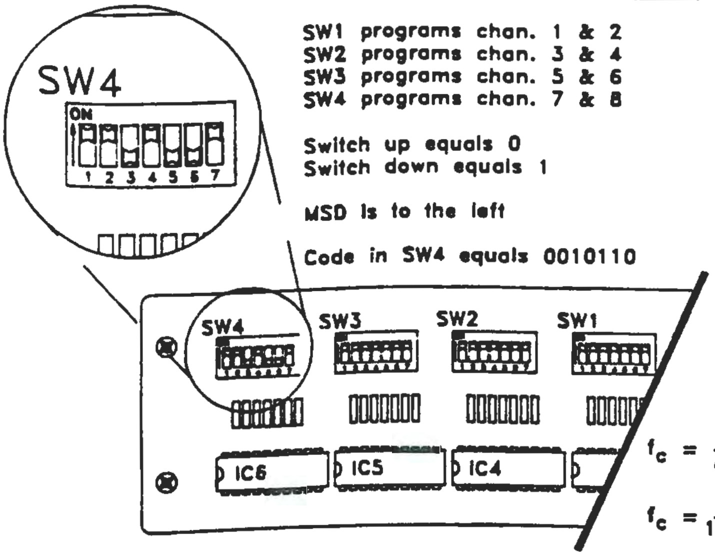
PROGRAMMING INFORMATION

SW1 programs chan. 1 & 2
SW2 programs chan. 3 & 4
SW3 programs chan. 5 & 6
SW4 programs chan. 7 & 8

Switch up equals 0
Switch down equals 1

MSD is to the left

Code in SW4 equals 0010110



Programmed code (Decimal)	Programmed code (Binary)	f_c (kHz)
0	0000000	1.000
10	0001010	1.129
20	0010100	1.296
30	0011110	1.521
40	0101000	1.842
50	0110010	2.333
60	0111100	3.181
70	1000110	3.888
80	1010000	4.565
90	1011010	5.526
100	1100100	7.008
110	1101110	9.545
120	1111000	15.000
127	1111111	25.000

$$f_c = \frac{87.5}{87.5 - \text{Code}} \times 1\text{kHz} \quad \text{for codes 0–63}$$
(f_c =1kHz to 3.57kHz)

$$f_c = \frac{262.5}{137.5 - \text{Code}} \times 1\text{ kHz} \quad \text{for codes 64–127}$$
(f_c =3.57kHz to 25kHz)

Figure 5. Programming information for low-pass filter.

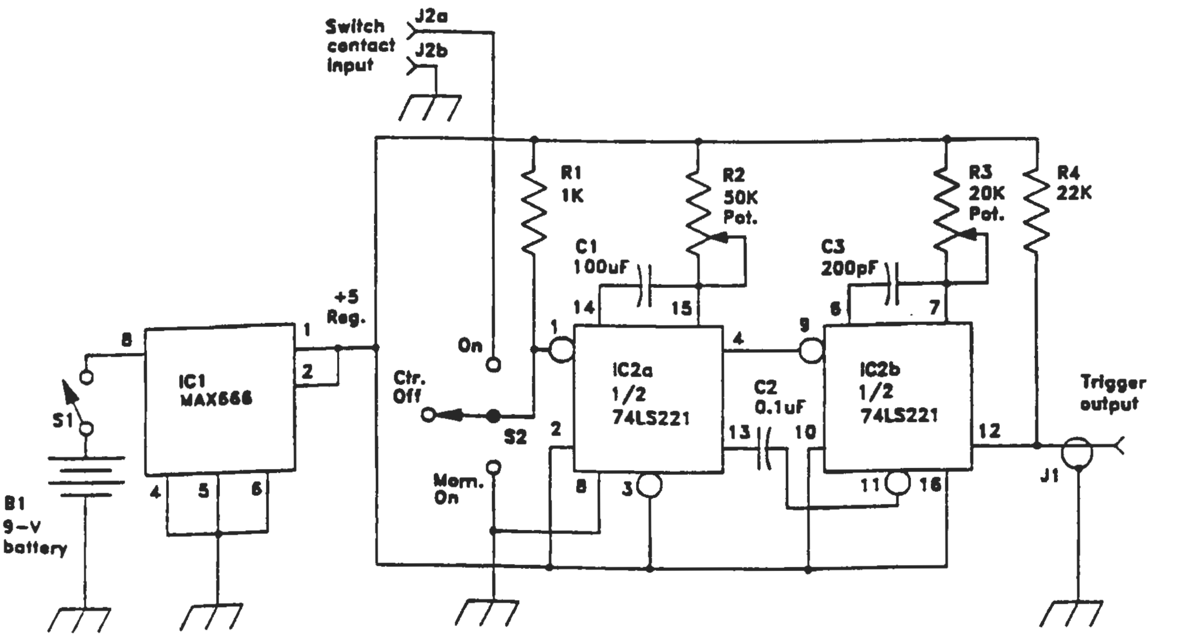


Figure 6. Electronic circuit for trigger box.

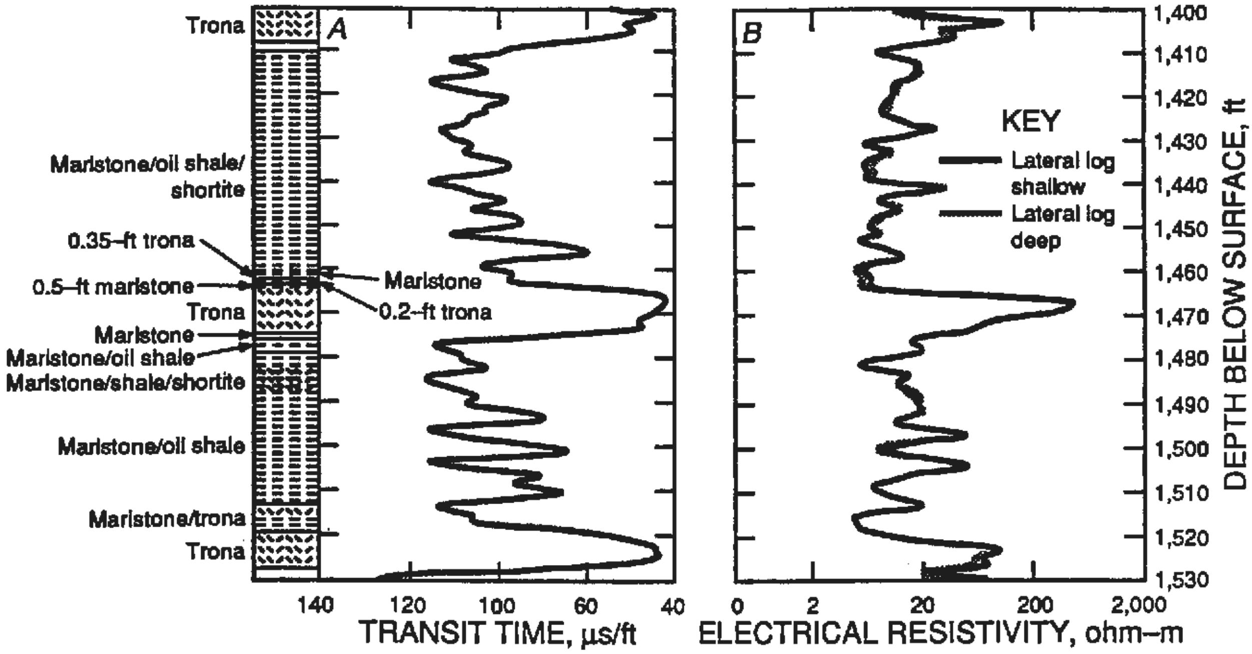


Figure 7. Typical well log.

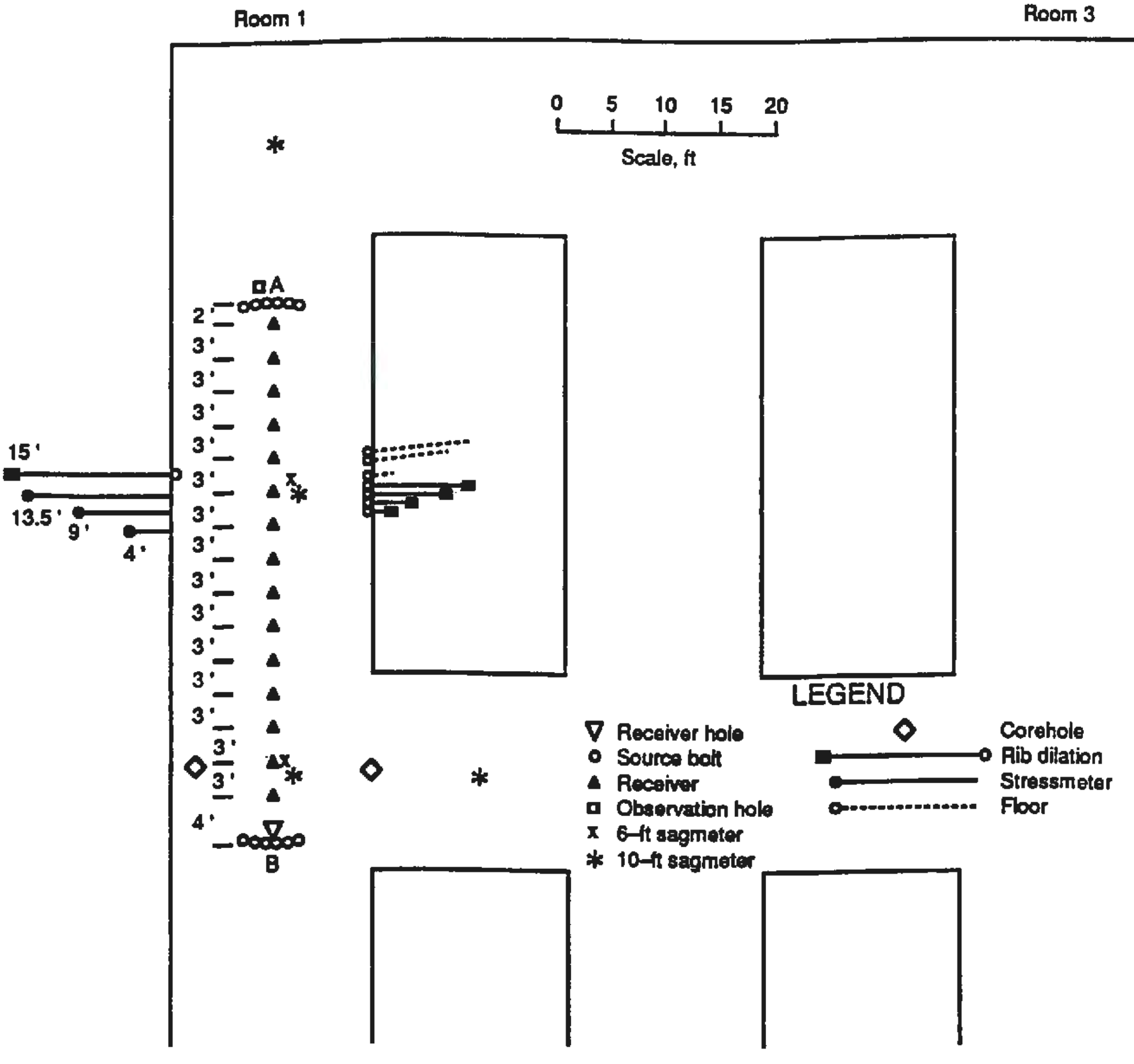


Figure 8. Plan view of instrument layout.

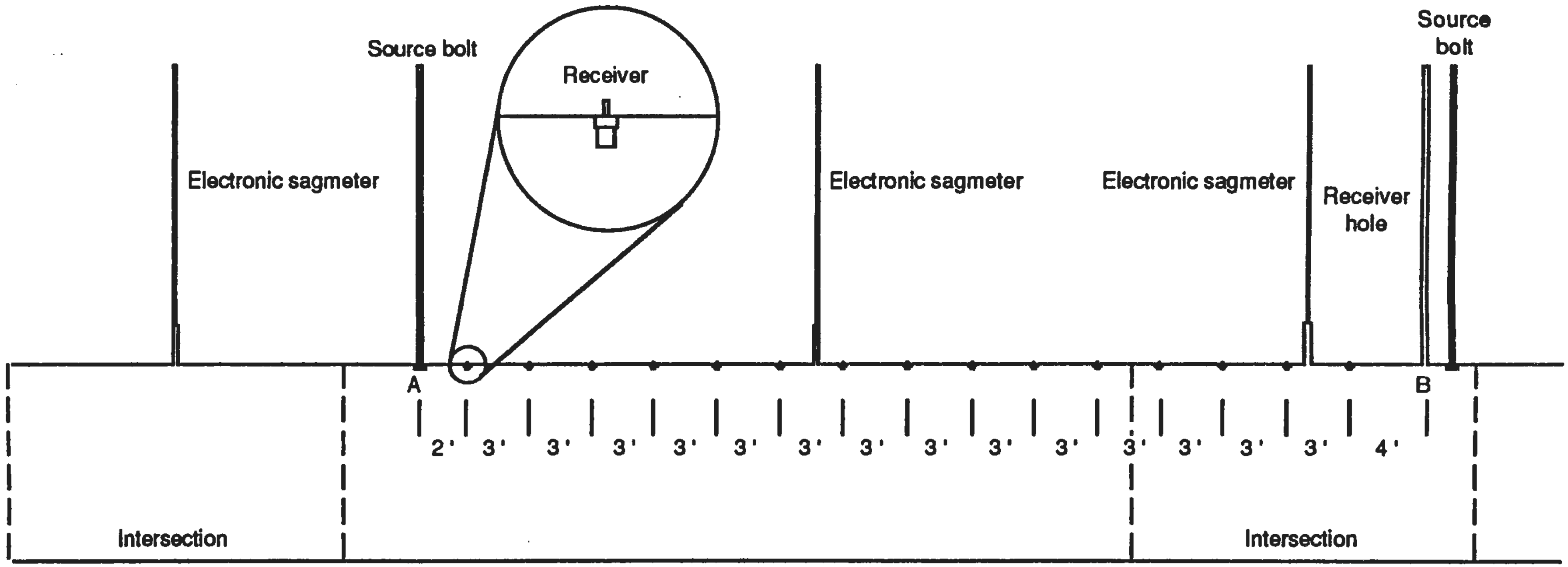


Figure 9. Instrumentation profile along seismic line A-B.

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