Borehole Investigation of Rock Quality and Deformation Using the 3-D Velocity Log

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ABSTRACT

The 3-D Velocity Log is a variable density presentation of the total wave train including P- and S- wave energies propagated along the boundary between the fluid and solid in a borehole. Reliability of field measured 3-D Velocity data has been verified in comparison with laboratory measured velocities. As a result, the computed dynamic elastic moduli favorably compare with laboratory determined dynamic moduli. Information obtained using this tool is used to investigate rock quality and deformation. Single well logging is used for investigating fracture and deformation around the borehole and dual well logging is used to investigate interwell rock quality. Specific field examples related to fractures and cavern detection and roof-rock deformation as a function of time are discussed.

INTRODUCTION

In recent years, new techniques and concepts of in situ field testing with the 3-D Velocity logging technique have been successfully employed to investigate problems that require a knowledge of rock quality and deformation. The 3-D Velocity system acquires a full complement of elastic waves including compressional, shear, and boundary waves. The additional information on the bulk densities of rocks obtained by the Formation Density Log (FDL) allows the determination of Young's Modulus and other elastic constants.

This paper discusses some of the comparison studies made of the field measured 3-D Velocity log and laboratory measured core velocities using the pulse technique. The measuring system employed in the laboratory is capable of measuring sequentially the compressional, and shear wave velocities of rock specimens under simulated borehole conditions. The Young's Modulus determined from the 3-D Velocity log is related to rock quality and deformation. The variation of the Young's Modulus as a function of time may indicate the weakening of cavern roof rocks.

The Dual well logging technique is employed to investigate rock quality between two holes. Using this technique the transmitter is placed in one hole and the receiver placed in an adjacent hole. The competency and homogeneity of the material between the two holes can be evaluated in this manner.

THE 3-D VELOCITY LOGGING SYSTEM

The downhole velocity logging tool shown schematically in Figure 1 has the transmitter and the receiver separated by an acoustic isolater. Figure 2 shows a P-wave front on the left and an S- wave front on the right. The distance between successive wave front lines represents the distance traveled in 100 microseconds in the fluid

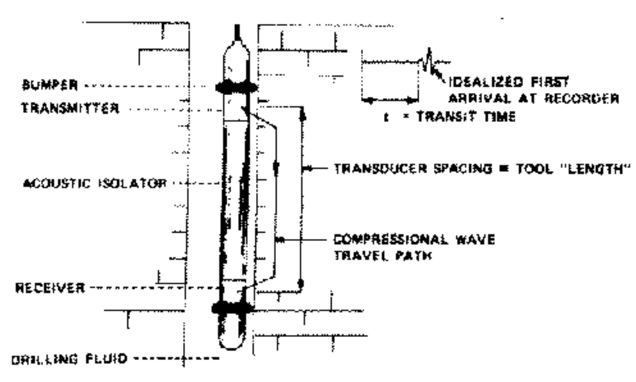


Figure 1. Downhole velocity logging tool.

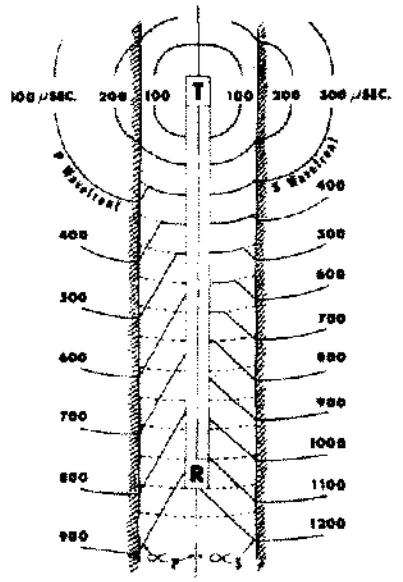


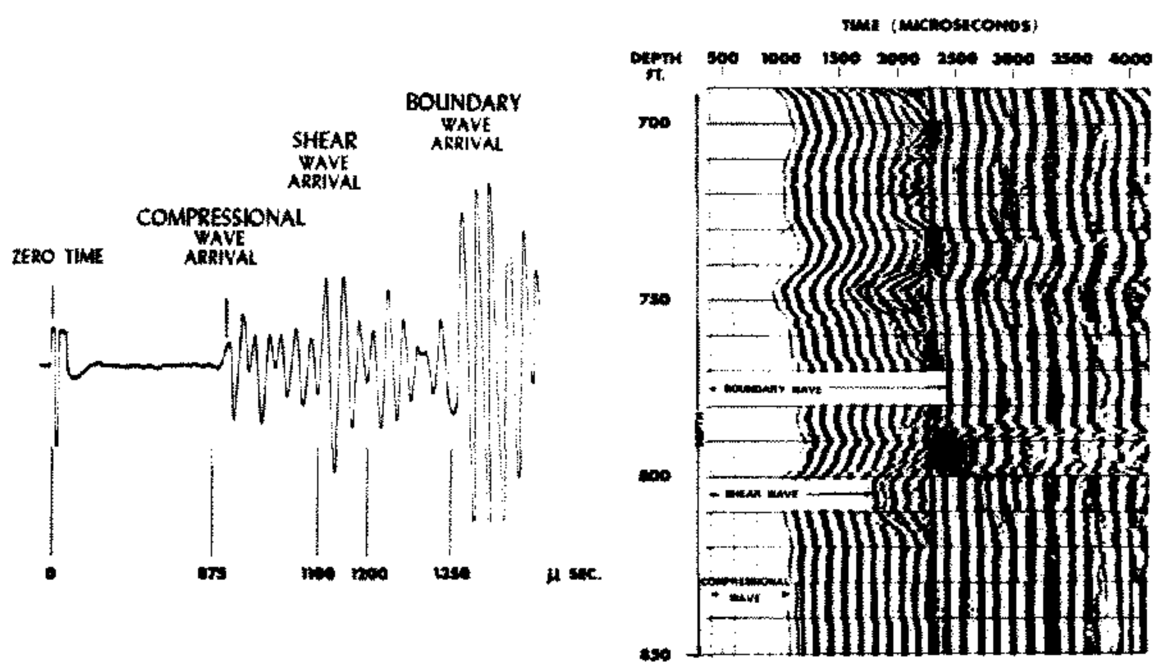
Figure 2. Wavefronts.

and the solid. The transmitter generates a short sinusoidal pulse of (20 khz/sec) about 20 times per second. Depending upon its initial direction from the transmitter, the energy will follow different paths through the fluid and borehole wall to the receiver. The changes in pressure detected by the receiver are transformed into an electrical signal which is transmitted to the surface where it is amplified, viewed on a cathode-ray oscilloscope, and recorded by the 3-D camera.

Figure 3 (a) depicts a typical variable deflection trace shown on the scope. The labeled events show clearly the characteristic amplitudes of the compressional, shear, and boundary wave events. Transit times are 875, 1100, and 1350 microseconds respectively. The intensity of the beam is modulated to produce a variable density on the 3-D camera film as shown in Figure 3 (b). Figure 4 illustrates an excellent repeatability of two 3-D Velocity log run on the Salina Salt Section before and after casing was run. Distortion indicated in the salt sections on the open hole 3-D Velocity log disappeared after cementing. This change is probably due to fractures in the salt section being sealed off in the cementing process.

LABORATORY APPARATUS

The laboratory method employed involved the transmission of compressional and shear waves through rock specimens subject to triaxial pressure. This measuring system (Myung and Helander, 1972) is capable of isolating the compressional and shear transducers, and of measuring sequentially complete wave trains of both compres-



(a) VARIABLE DEFLECTION TRACE

NOTE: TRANSIT TIMES ESTIMATED FROM FIG. 3a TO ILLUSTRATE WAVE CHARACTERISTIC

(b) 3-D VELOCITY LOG

Figure 3. Signal Displays.

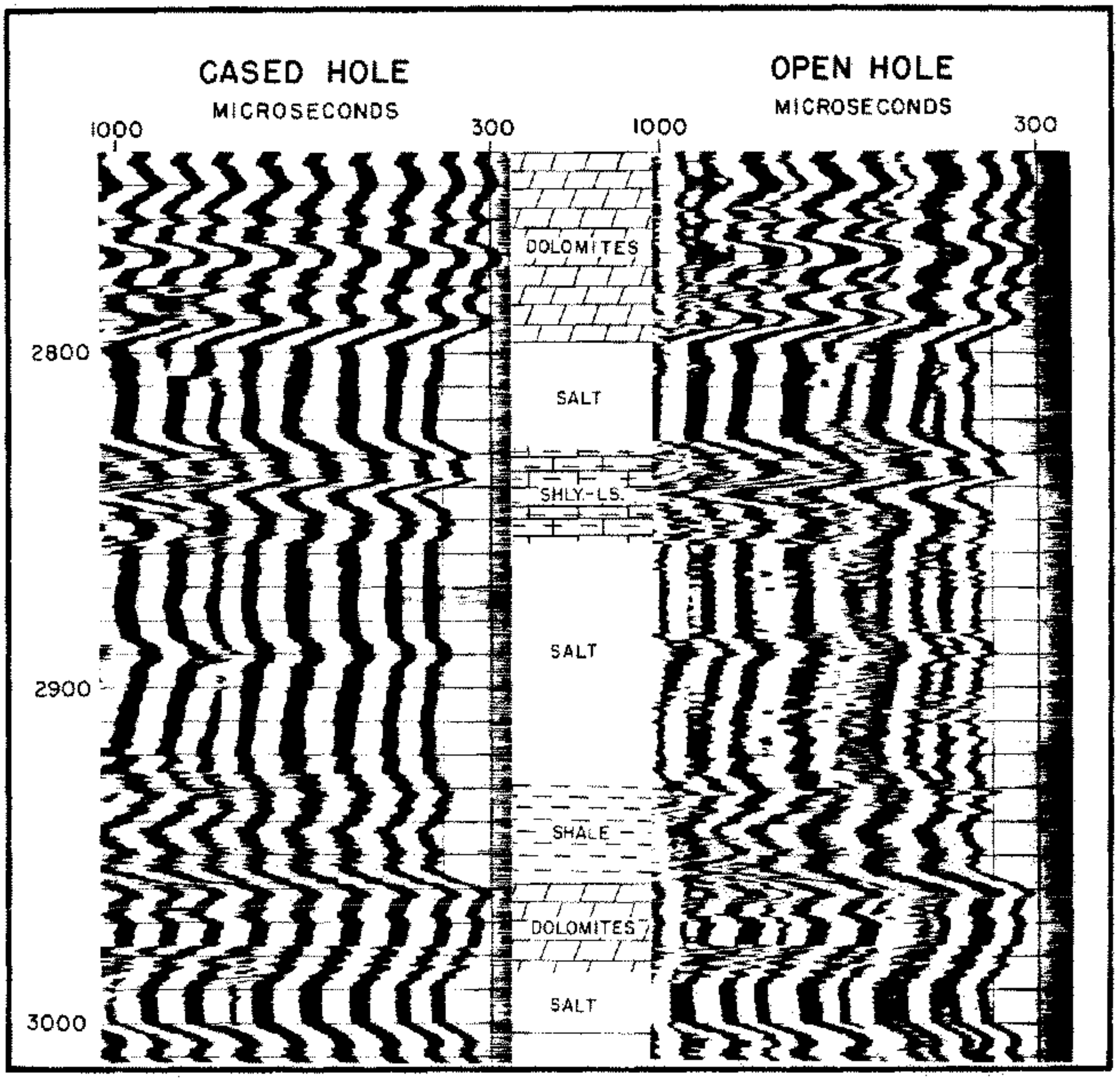


Figure 4. 3—D Logs Run in Cased Hole and Uncased Hole.

sional and shear waves. With this system, rock sample velocities can be measured to an accuracy of 1%. As shown in Figure 5, the rock sample is placed in the pressure chamber where both over-burden and internal rock pressure can be applied to simulate the subsurface conditions matching those from where the core sample is taken. The piston and jacket pressure represent an overburden pressure, and the fluid pressure simulates the formation pore pressure. Fifteen core samples were taken from granite, gabbro, tuffs, and sandstone from 11 different wells located in various states. Figure 6 shows the comparison of the compressional and shear wave velocities obtained from the 3-D Velocity log and from the laboratory measuring system. A least-square method to determine a straight line through the data verifies the reliability of field measured 3-D Velocities when compared with the laboratory measured velocities.

ELASTIC PROPERTIES OF ROCKS

New techniques and concepts of field testing with 3-D Velocity logging procedures make it possible to determine the in situ elastic properties of rocks which have been penetrated by the drill. This procedure is superior to laboratory tests which do not duplicate in situ conditions.

The fundamental elastic theory of Hooke's Law is that

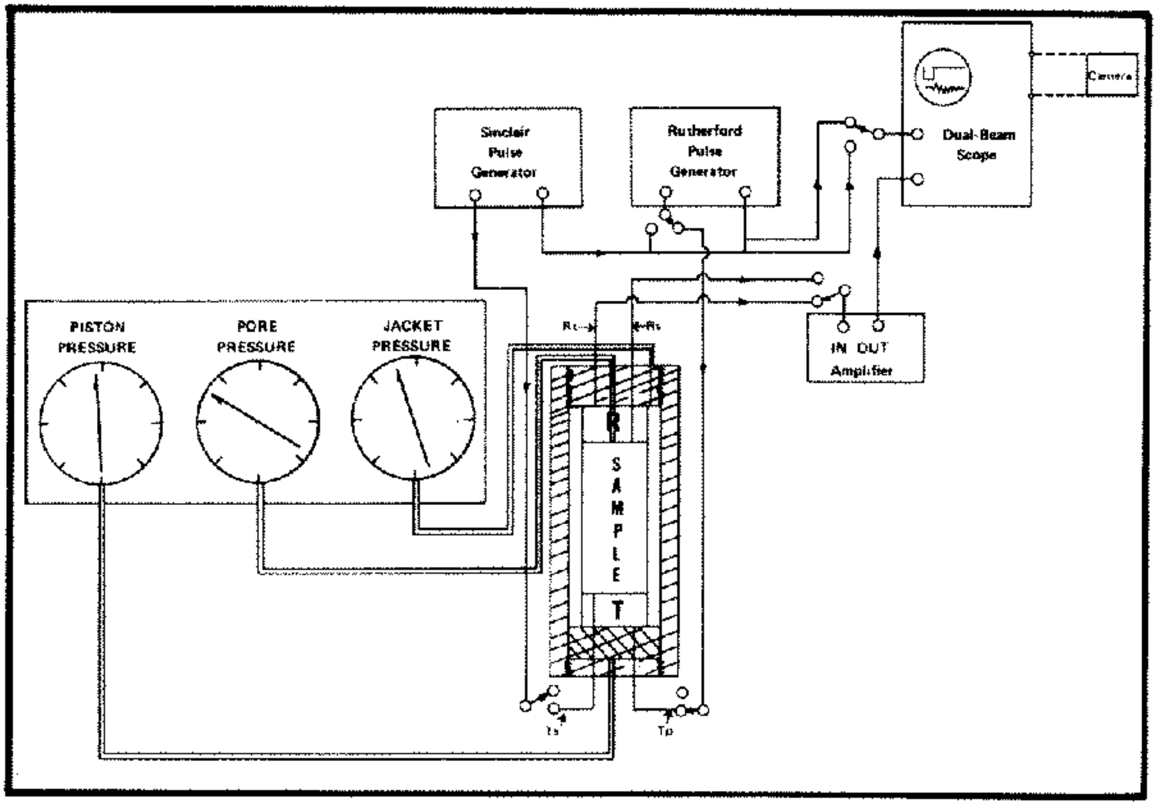


Figure 5. Laboratory Measuring System.

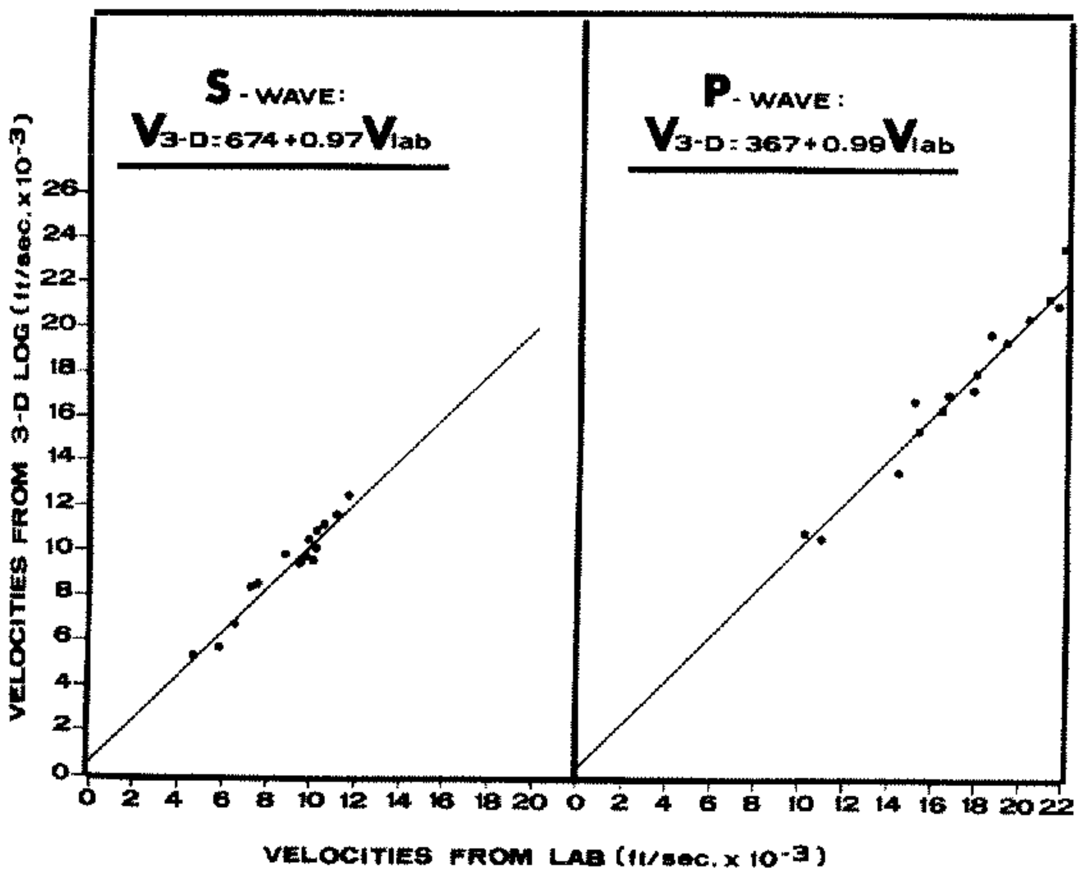


Figure 6. Comparison of Velocity Measurements.

stress is directly proportional to strain and is linearly related. Thus, all strain is recoverable on the removal of the stress from material that fulfills the requirements of Hooke's Law. In dealing with rocks, some of which do not meet the full requirements, there will be less than total recovery. However, in engineering applications, the theory of elasticity has been assumed to be valid for the combination of rocks discussed in this paper. Thus, the theoretical relationships developed for homogeneous and isotropic materials have been systemically used to compute the elastic constants from velocity and density measurements of rocks. The mathematical relationships to determine the elastic constant of homogeneous isotropic, and elastic solid are shown in the following equations:

Poisson's Ratio $$\nu=\left[0.5\left(\frac{V_p}{V_s}\right)^2-1\right]\Big/\left[\left(\frac{V_p}{V_s}\right)^2-1\right] \quad (1)$$

Shear Modulus $$\mu=\rho V_s^2 \quad (2)$$

Young's Modulus $$E=2\mu(1+\nu) \quad (3)$$

Bulk Modulus $$B=\rho V_p^2-\frac{4}{3}\mu \quad (4)$$

where: V_p=P-wave Velocity
V_s=S-wave Velocity
ρ =Density

The variation of elastic moduli with external pressure for dry specimens of Berea sandstone is shown in Figure 7. The acoustic velocity in the dry sample is more sensitive than in the saturated specimen. This behaviour shows that water is effective in coupling the pulse across microfractures at low stress levels. It also indicates that Young's Modulus is more sensitive to external pressure than other elastic moduli. For this reason Young's Modulus values are primarily used in rock mechanics work for indicating the rock strength.

The histogram in Figure 8 illustrates a comparison of Young's Modulus (E) determined from the 3-D Velocity log with values measured in the laboratory using the pulse technique method. It shows good agreement between the two sources of measurements since the rock specimens studies were fairly competent and homogeneous. Young's Modulus determined from the 3-D velocity log was also related to deformation modulus obtained from Goodmen Jack Test (Stowe, 1972) from four wells as shown in Figure 9. A least-square method was used to determine a

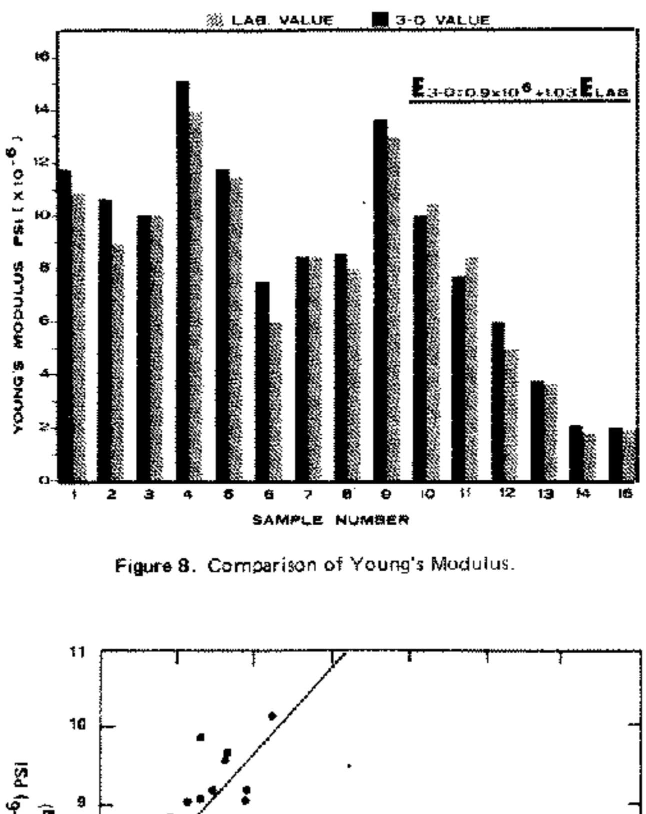


Figure 8. Comparison of Young's Modulus.

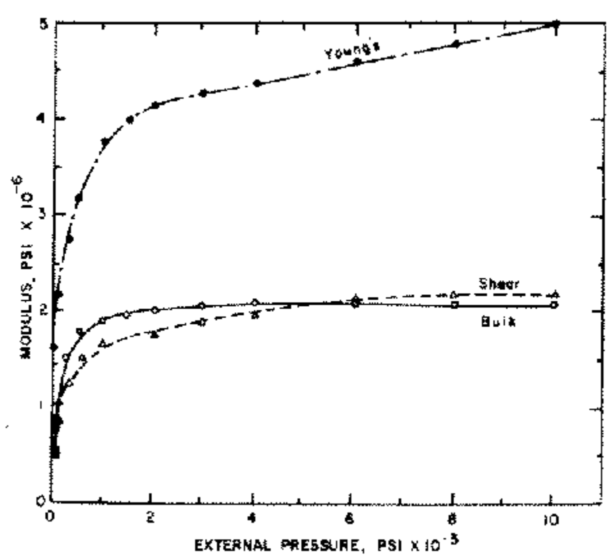


Figure 7. Elastic Moduli vs. External Pressure.

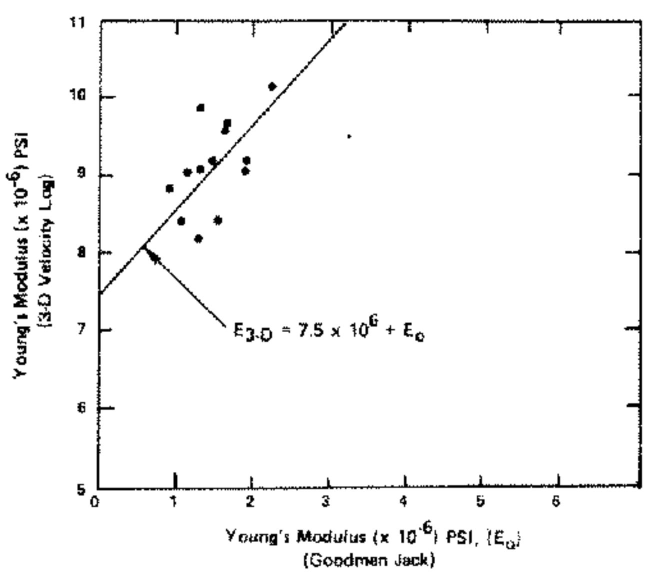


Figure 9. Comparison of 3-D Measurement and Goodmen Jack Tests.

straight line through the cluster of points to check the linearity of comparison. It is interesting to note that Young's modulus determined from the 3-D Velocity log is consistantly 7.5 X 10^6 psi higher than the results obtained by the Goodmen Jack tests. Results of other plate jacking tests show that the modulus measured in rock mass is always smaller than the static modulus determined from intact core sample or the dynamic modulus determined by either the pulse technique or the 3-D Velocity method.

SINGLE WELL LOGGING TECHNIQUE

The primary input to the computer programs that determines the elastic properties is digitized from the 3-D Velocity, Formation Density and Caliper Logs. The program computes the corrected compressional and shear velocities; the Shear, Bulk, and Young's moduli and Poisson's Ratio. Figure 10 illustrates a combination of field logs with the computed elasticity log run on the Salina Salt section of Silurian age. It is interesting to note that actual subsidence took place in this brine well in Michigan. Extremely low elastic moduli are shown at the interval between 920 ft. and 1110 ft. for the roof rocks above the solution cavern.

Roof rock subsidence studies

Figure 11 illustrates a sample log consisting of Gamma-Ray, Formation Density, 3-D Velocity log, and Young's Moduli plots[5] in time. These surveys were made in a brine well to investigate the fracturing and subsequent displacement and weakening of the roof rocks over the cavern developed in solution salt mining operations. 3-D Velocity logs were systematically run every year in the same hole since 1968 to make correlation studies on the Young's Modulus values of the roof rocks. Four Young's Moduli were superimposed to observe the rate of variation on Young's Modulus as a function of time. Decrease in Young's Modulus of the overlying rocks is shown in Figure 11 between Run 1 (1968) and Run 4 (1971), especially for Interval A. These changes in Young's Modulus could be caused from fractures and fissures being developed in the rock mass. The Caliper survey indicated a casing split at the bottom casing collar. This technique may make possible the determination of the weakening of roof rocks over mines, caverns and tunnels, with the object being the prediction of the time of total collapse.

Rock strength classification

A proposed rock classification method was developed relating Young's Modulus and rock density using the 3-D Velocity and Formation Density Logs. The boundary conditions for the rock classification were emperically assumed as shown in Table I. A cross-plot program was performed by the computer using the given boundary conditions. The Rock Index numbers (Myung and Helander, 1972) were plotted graphically as shown in Figure 12.

It is interesting to note that the slope of the Rock Index follows a 45 degree trend, and the strength of the rock decreases with an increase of the Rock Index numbers. The use of this classification system can be of practical value since Young's Moduli and rock densities can be obtained directly from the 3-D Velocity and Formation Density Logs which are readily obtained in the field.

Rock quality designation

Rock Quality Designation (R.Q.D.) is the ratio of the cumulative length of the unfractured core to the unit

ROCK INDEX NO.	DESCRIPTION	CONDITION
1	Very Hard	$E > 10 \times 10^6$ $D > 2.76$
2	Hard	$7 \times 10^6 < E < 10 \times 10^6$ $2.60 < D < 2.76$
3	Medium	$5 \times 10^6 < E <$ [illegible] $\times 10^6$ 2.[illegible] $< D < 2.59$
4	Soft	$3 \times 10^6 < E <$ [illegible] $\times 10^6$ 2.[illegible] $< D <$ 2.[illegible]
5	Very Soft	$E < 3.0 \times 10^6$ $D < 2.2$[illegible]

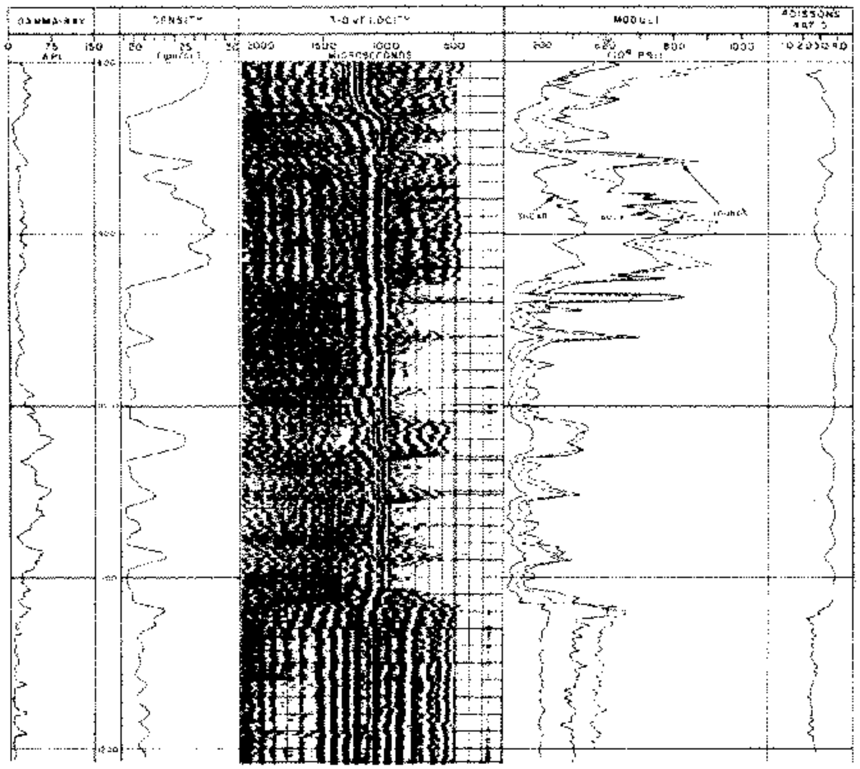


Figure 10. Field Logs and Elasticity Log.

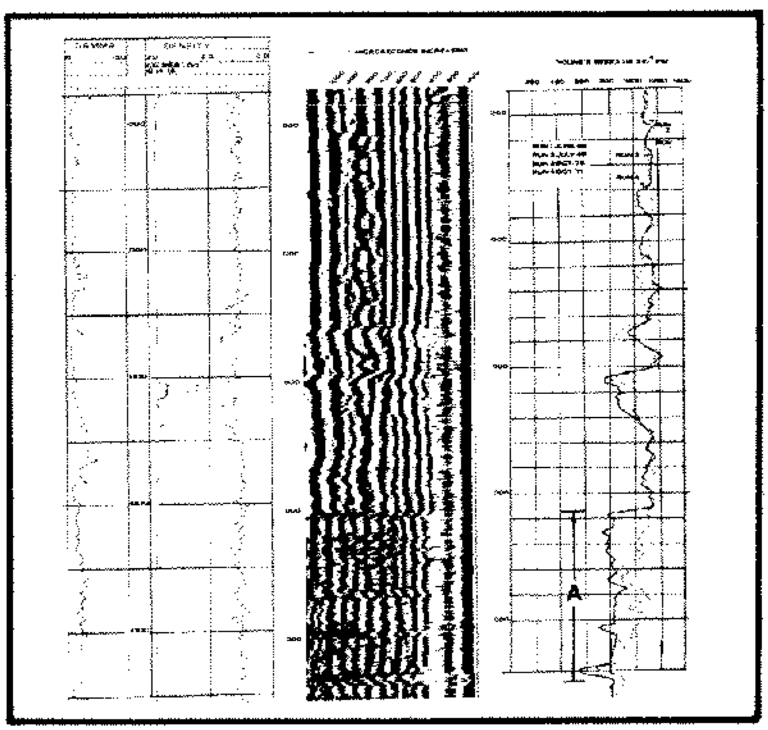


Figure 11. Gamma-Ray, Density, 3–D Velocity Logs and Young's Modulus Plots.

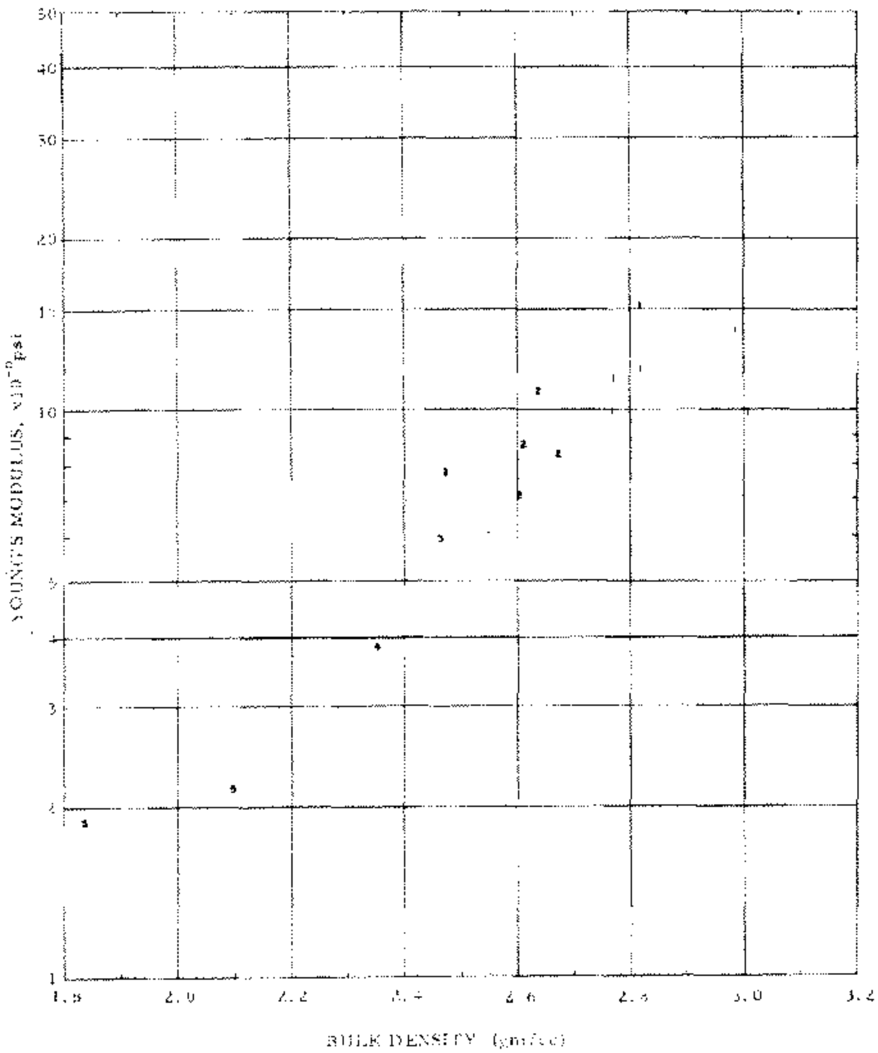


Figure 12. Young's Modulus Versus Density Plot.

length of the core. Figure 13 illustrates a comparison of core characteristics, R.Q.D., elastic properties and the 3-D Velocity log for a continuous 95 feet section of igneous rocks (Geyer and Myung, 1970). Note the marked similarity in general shape of elastic moduli curves and R.Q.D. plots. Elastic moduli clearly delineates the 50% R.Q.D. zone by abnormally low values. The 3-D Velocity Log also shows the fractured low R.Q.D. zone by the small amplitude and long transmit time of the P and S waves.

Fracture investigation

Figure 14 is a 3-D Velocity log from granite in New Hampshire. In zone C of this log, the compressional wave is not attenuated while the shear wave amplitude is severely reduced due to low angle horizontal fractures or bedding planes. The strong energy arrivals for both compressional and shear waves in zone B indicate that no fracture is present.

The reflected energies from fractures or bedding planes are continuously recorded. These energy waves are indicated as Diagonal Energy Transmission in Figure 14. The experimental data of Dzeban (1970) and Knopoff and MacDonald (1958) regarding the attenuation of amplitude of both the compressional and shear waves across fractures seem to compare satisfactorily with the field results obtained by the 3-D Velocity log.

Cavern investigation

Another interesting investigation was made where an observation hole was drilled near another hole in which a small nuclear device was detonated in a salt dome. As shown in Figure 15, the compressed scale 3-D Velocity log run in the observation well (Lawrence, 1965) illustrates what is believed to be reflected boundary energy of considerable magnitude from the cavern. The general shape of the cavern and the distance from the observation hole to the cavern can be estimated from this log.

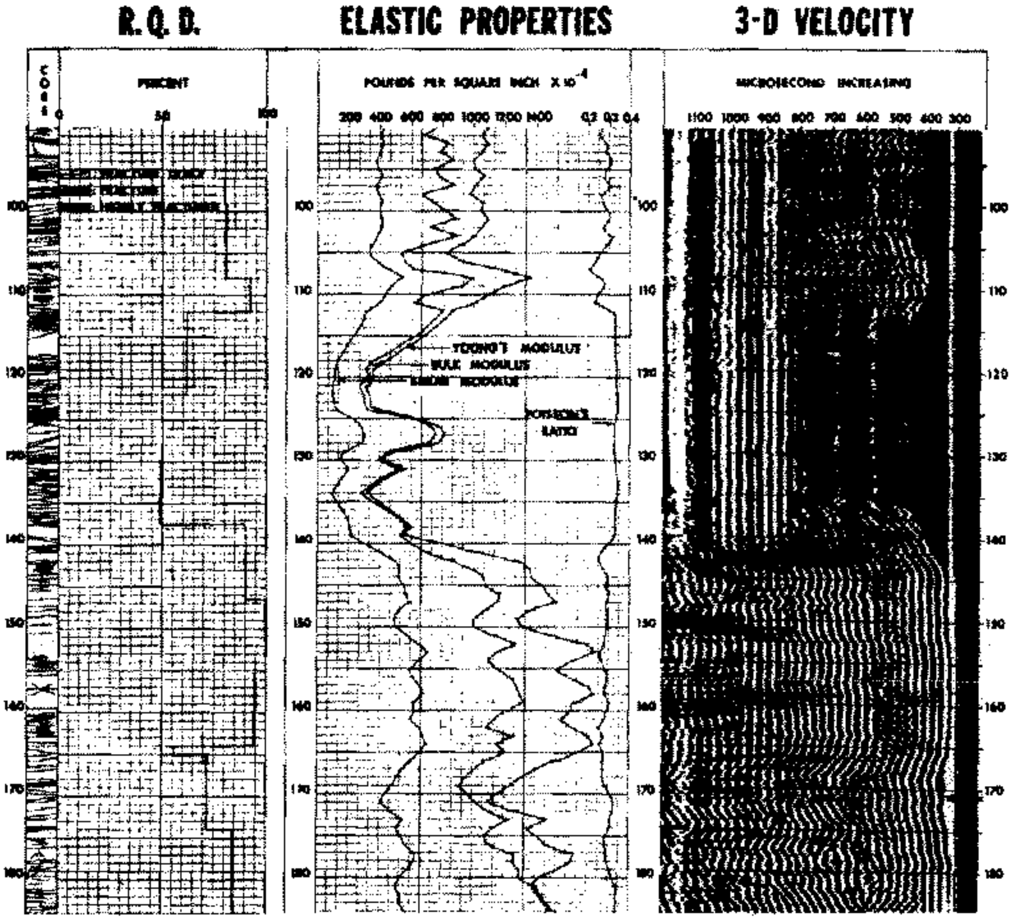


Figure 13. Comparison of R.Q.D., Elastic Properties and 3–D Velocity Log for 90-185 ft. section of corehole.

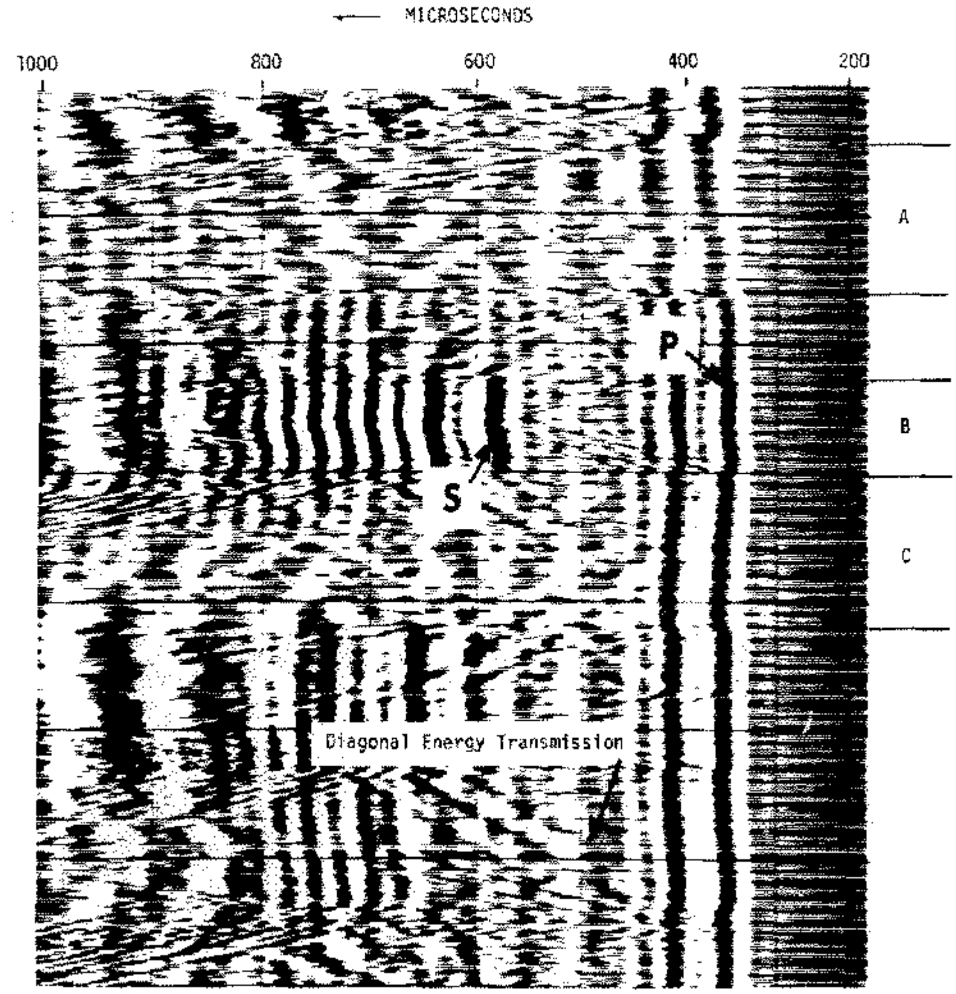


Figure 14. 3-D Velocity Log in Granite.

DUAL WELL LOGGING TECHNIQUE

There is further application of the 3-D Velocity logging procedure which is of use in rock quality investigation. This is the dual well logging or hole-to-hole technique. In this, the transmitter is placed in one hole and the receiver placed in an adjacent hole. Both transducers, transmitter and receiver, move up or down their respective holes at the same level and at the same rate. The transmitted acoustic signal travels horizontally. The competency and homogeneity of the material between the two holes can, therefore, be evaluated by studying the compressional wave arrivals. In this technique, only the compressional wave energy is recorded since both the transmitter and receiver are placed at the same horizontal level, and as a result, no mode conversion of wave energy takes place because no refracted wave energy is recorded at the receiver. In order to receive the shear wave energy between the two holes, the transmitter is maintained at one depth, as the receiver is moved upward in the other hole. This procedure is referred to as the "Stationary Transmitter" Dual Well Logging Technique.

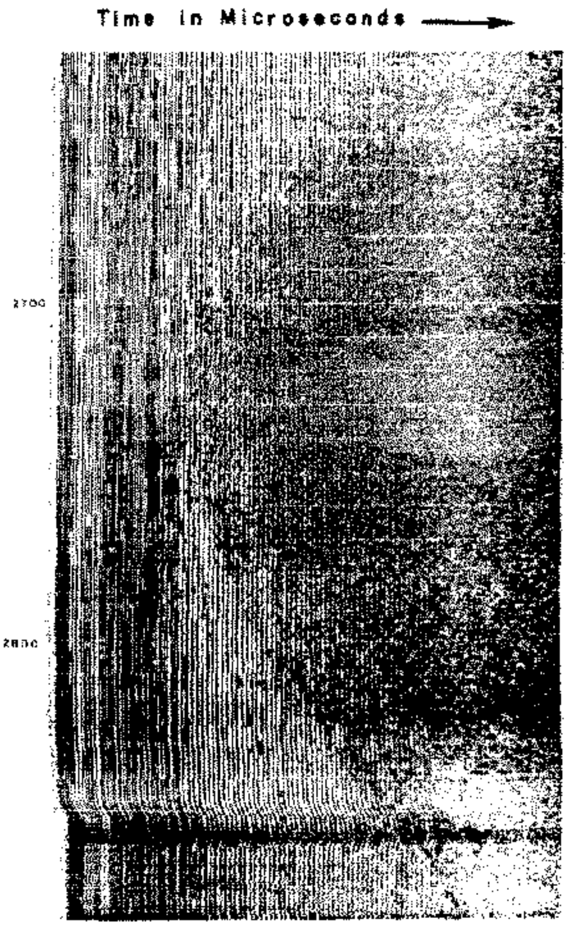


Figure 15. Reflected Boundary Energies Recorded by 3-D Velocity Log.

Fracture investigation

Figure 16(a) and (b) illustrates the actual 3-D Velocity log recorded by single and Stationary Transmitter dual well logging techniques in an Oklahoma limestone section. In Figure 16(b) the transmitter remained at a depth of 25

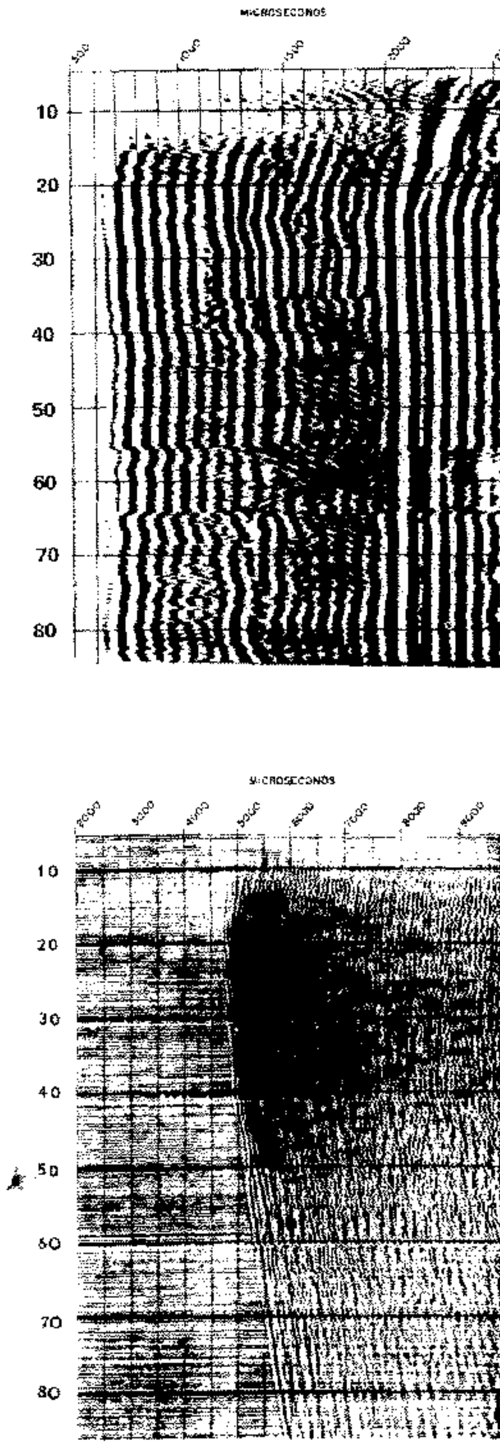


Figure 16. (a) Single Well Technique. (b) "Stationary Transmitter" Dual Well Logging Technique.

feet in one hole and the receiver moved up the hole in the adjacent well. The horizontal distance between the two holes was approximately 120 feet. The signal distortion indicated at the depth of 60 feet is due to the presence of a clay seam, which can be observed on both logs.

Figure 17 is another 3-D Velocity log using the Dual Well technique. The interval between 33 to 38 feet shows the attenuation of the acoustical signal due to an incompetent zone. This technique can be used to locate caverns in limestone between two holes.

A log using the Stationary Transmitter Dual Well logging technique (Myung and Baltossen, 1971) is shown in Figure 18. The transmitter is placed at 65 feet, as the receiver is moved upward from 100 to 30 feet in the adjacent hole. The compressional wave distortion in the interval at 30 to 40 feet indicates a fractured zone. This technique may be used to investigate shear wave velocity in low velocity materials. The distortion showing on the P- wave at 37 feet indicates the fractured zone.

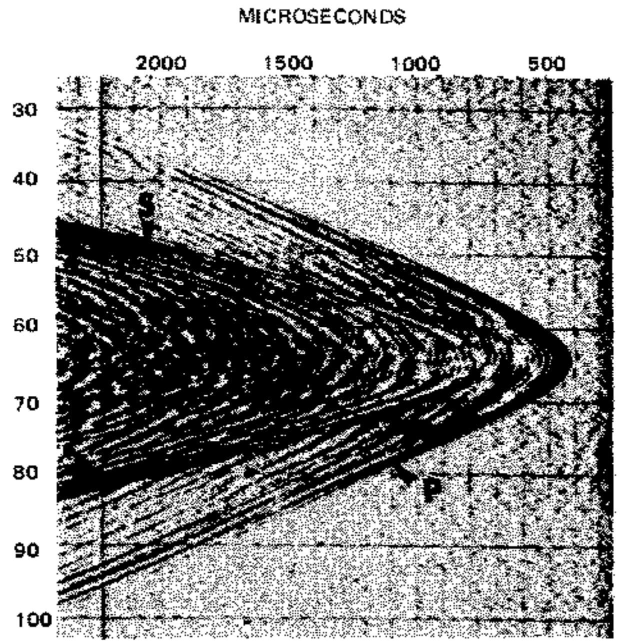


Figure 18. "Stationary Transmitter" Dual well log showing P-and S-waves.

CONCLUSIONS

Comparison studies of 3-D Velocity data with laboratory measured data indicate that the 3-D Velocity system can provide in situ measurements with sufficient accuracy to be of practical use in the field. The Young's Modulus computed using 3-D Velocity log data can be related to stress variation, deformation and quality of rocks. Further experimentation and research are needed for cavern detection using the technique of recording reflected boundary energies. Dual well logging techniques can be useful for investigating the competency and homogeneity of the rock between the two holes.

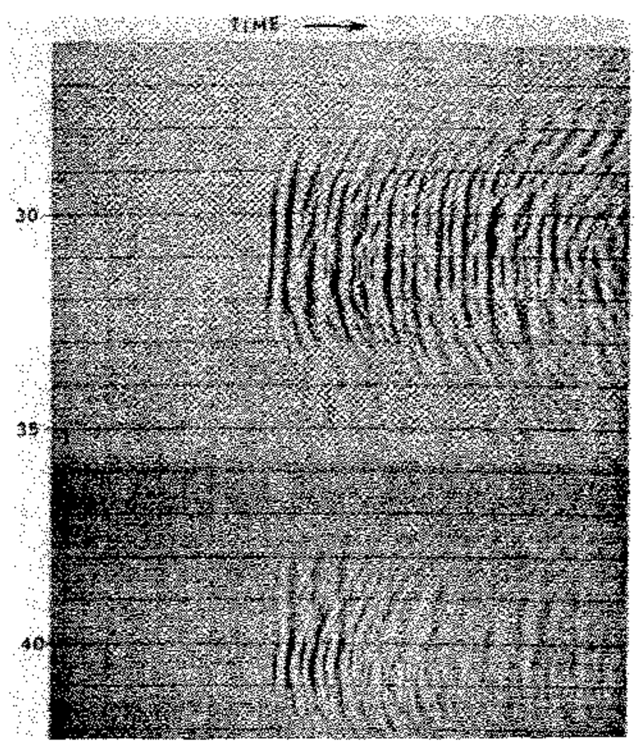


Figure 17. Dual well log showing competent and incompetent zones.

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