1966

The development of the sonic pulse technique and its comparison with the conventional static method for determining the elastic moduli of rock

James Harold Deatherage

THE DEVELOPMENT OF THE SONIC PULSE TECHNIQUE AND ITS COMPARISON WITH THE CONVENTIONAL STATIC METHOD FOR DETERMINING THE ELASTIC MODULI OF ROCK

BY

JAMES HAROLD DEATHERAGE, JR.

A

THESIS

submitted to the faculty of

THE UNIVERSITY OF MISSOURI AT ROLLA

in partial fulfillment of the requirements for the

Degree of

MASTER OF SCIENCE IN MINING ENGINEERING

Rolla, Missouri

1966

Approved by

Charles J. Haas (advisor) Gerard B. Rupert

R. F. Davidson Peter G. Hansen

ABSTRACT

The determination of the elastic moduli of rock has long been a problem to the geophysicist, mining engineer and the civil engineer. There is a considerable amount of literature on determining Young's modulus by the sonic pulse technique. However, the use of this technique to determine the three elastic constants, Young's modulus, shear modulus, and Poisson's ratio from measurements of both the longitudinal and shear wave velocities presents some difficulties, especially in the method of accurately determining the shear wave velocities.

In this thesis, what is believed to be a new method of measuring shear wave velocities in the laboratory is developed and used with the conventional method of measuring the longitudinal wave velocity to determine the three elastic constants of four rock types. These results are then compared to those obtained by conventional static methods for determining elastic moduli, with the effect of anisotropy of the rocks being considered.

The results by the two methods were in fair agreement for Young's modulus and the shear modulus, however, large unexplained variations in Poisson's ratio were often observed.

ACKNOWLEDGEMENTS

The author wishes to express his thanks to Dr. Charles J. Haas without whose advice this thesis could not have been possible; to Fredrick Smith for the petrographic description of the rock types used; to his wife, Barbara Deatherage, for typing.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

The purpose of this research was to develop some techniques for accurately determining the elastic moduli of rock. The techniques employed are the sonic pulse method and the conventional static method.

Non-destructive testing is used extensively in industry as a method of detecting flaws in elastic materials. Recently the method of non-destructive testing has become popular in determining the elastic constants of various materials. Extensive research has been done in determining the elastic properties of rock. In 1946 the Bureau of Mines found that a great deal of work had been done in determination of rock properties but that very little data had been published. Since that time nearly every major research group has conducted some work on the elastic properties of rock. However, many questions are still unanswered as to the reliability of and the ability to duplicate certain tests. A brief discussion follows concerning the two major types of sonic testing and the method of static testing that is recommended by the Bureau of Mines. The synopsis of sonic methods is taken from Jones' (4) Non Destructive Testing of Concrete.

Longitudinal Resonance Method

The beam is supported at its midpoint. A vibration generator and a piezo-crystal pick-up are placed in contact with opposite ends of the beam. It is essential in this method that the ends of the beam are not supported or constrained in any way so that the ends are free to vibrate. Therefore the vibrator and the pick-up must be designed so as to minimize the end constraint. Also the beam must be long compared to its cross-sectional dimension.

As the frequency of the vibrations is varied, the beam will reach a resonant frequency. At this resonant frequency, the amplitude of the vibrations will be a maximum. For the lowest natural frequency the midpoint of the beam will be a nodal point. That is, the amplitude of the vibrations at the midpoint is zero. The lowest frequency at which resonance occurs is the fundamental longitudinal resonant frequency (f_L). The relation of this frequency to dynamic Young's modulus is as follows:

$$E = 4(f_L)^2 \, l^2 \rho$$

where ρ is the mass density of the material, and l is the length of the specimen. The above equation is derived for a perfectly elastic, isotropic, homogeneous, semi-infinite beam. Bancroft (4) derived a solution for the variation in the dynamic Young's modulus for finite beams. This variation is dependant upon the wave length of the vibration, the diameter of the cylinder, and Poisson's ratio. Bancroft's corrections for the longitudinal vibration of cylinders is shown in Figure 1.

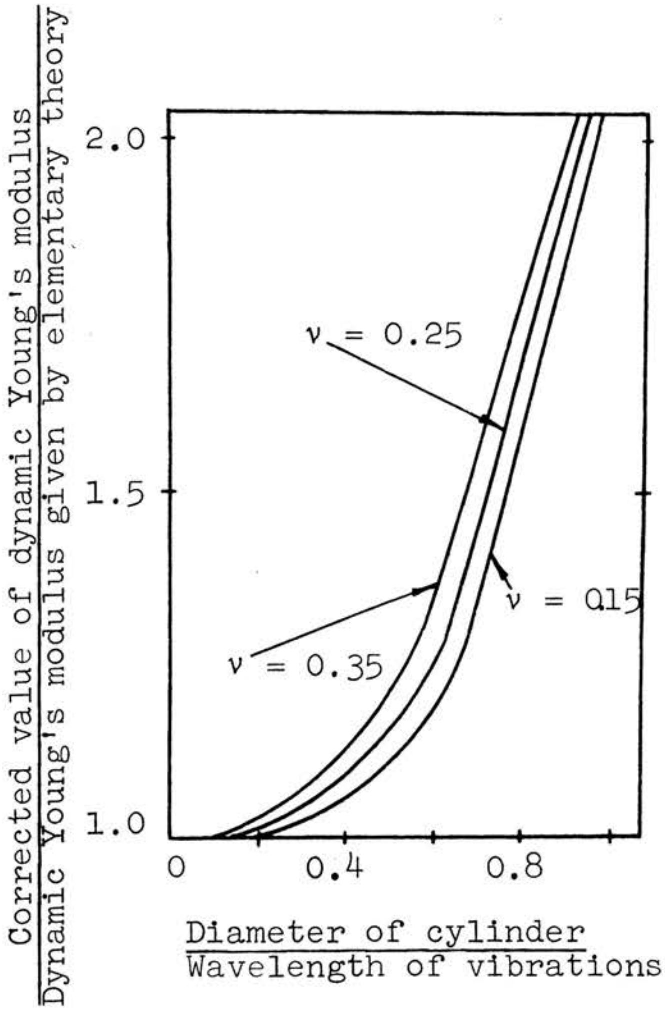


Figure 1 Bancroft's Corrections for Longitudinal Vibration of Cylinders

Torsional Resonance Method

Torsional resonance is achieved by placing the vibrator in such a position as to induce the maximum torque on the specimen. For a rectangular beam the vibrator is usually placed at one corner of the specimen, while the pick-up is placed at one of the corners on the opposite end of the specimen. The nodes and antinodes of the vibrations occur at the same positions as for the longitudinal vibrations. The dynamic shear modulus μ as derived by Pickett (4) is given by the relation

$$\frac{\mu}{\rho} = 4(f_t)^2 l^2 \frac{(a/b) + (b/a)}{(4a/b)^2 - 2.52(a/b)^2 + 0.21(a/b)^6}$$

where f_t is the fundamental torsional frequency, a is the width of the beam, and b is the depth of the beam. For the cylinder the relation is

$$\frac{\mu}{\rho} = 4(f_t)^2 l^2$$

Pulse Methods

Three common methods of generating pulses in materials are by an explosive, by a hammer blow, and by an electro-acoustic transducer. The explosive and the hammer blow methods impart a considerable amount of energy into the medium and consequently the wave can be transmitted over longer distances if damage to the specimen is tolerable.

When an impulsive force is applied to a free surface of a semi-infinite solid, four types of waves may be generated.

The fastest of these waves is the longitudinal or P wave in which the particle motion is parallel to the direction of propagation. The longitudinal wave velocity V_L is given by the equation

$$V_L^2 = \frac{E}{\rho} \frac{(1-\nu)}{(1+\nu)(1-2\nu)}$$

where ν is Poisson's ratio for the material. The second fastest wave is the shear wave or S wave in which the particle motion is perpendicular to the direction of propagation. The velocity of the shear wave V_S is given by

$$V_S^2 = \frac{\mu}{\rho} = \frac{E}{2\rho\,(1+\nu)}$$

where μ is the modulus of rigidity of the material. A third type of wave generated is the Rayleigh wave. The particle motion of a Rayleigh wave is in the form of an inverse retrograde ellipse. The velocity of the Rayleigh wave V_R is given by

$$V_R^2 = \xi^2 V_S^2$$

where ξ is a function of Poisson's ratio. However ξ is always less than unity. Therefore the Rayleigh wave velocity will always be less than the shear wave velocity. A fourth type of wave which can be generated is the Love wave. The geometry of the experiments described in this thesis was such that Love waves were not generated since their formation requires the existance of an interface some distance below the free surface.

The electro-acoustic pulse method can be used to great advantage in the laboratory by using piezoelectric transducers provided enough energy can be transmitted into the material. The transducers in effect convert electrical energy into mechanical energy and vice-versa. The source transducer expands and contracts when subjected to applied voltage pulses. The expansion and contraction are transmitted to the specimen with the resulting particle motion being in the same direction as the expansion and contraction.

The propagation velocity of a particular wave can be determined from measurements of the travel distance and the corresponding travel time for that wave. From measurements of the longitudinal and shear wave velocities and the relationships between the elastic constants, it is then possible to determine the three elastic constants for the material.

The Static Method

The Bureau of Mines method (6) of determining the elastic constants is described herein. Cores, ranging in diameter from 7/8 in. to 2 1/8 in., may be used. The height to diameter ratio of the cores should be between 2.0 and 2.5. The ends of the cores are lapped and ground until the surfaces are flat and perpendicular to the main axis of the core. Electrical resistance strain gages are then mounted both longitudinally and laterally on the cores. The specimens are then loaded at a rate of 100 $lb/in^2/sec$ to approximately 50% of their compressive strength. Six complete loading and unloading cycles are then completed, with the data being taken on the seventh cycle. Stress-strain curves are then plotted from which Young's modulus and Poisson's ratio may be determined.

CHAPTER II

ROCK TYPE DESCRIPTION

The following is a petrological description of the rock types used in this research:

Georgia Granite	Location: Stone Mt., Ga.
Mineral Composition:	Quartz............ 35% Biotite........... 10% Orthoclase......... 50% Muscovite.......... 3% Hornblende......... 2%
Texture:	Hypidiomorphic, granular.
Shapes:	Biotite, Muscovite - euhedral Orthoclase, Hornblende - subhedral Quartz - anhedral
Structure:	No profound orientation of minerals.

Jefferson City Dolomite	Location: UMR, School Mine
Mineral Composition:	Dolomite........... 90% Calcite............ 10%
Gross Character:	Tan color, vuggy, massive bedding.
Texture:	Crystaline, irregular shaped grains of dolomite, no uniform shape or size, vugs are lined with calcite.
Matrix and Cement:	Mainly dolomite, some calcite present.
Fossils:	None

Platten Limestone | Location: Eureka, Mo.

Mineral Composition:	Calcite............ 80% Clay............... 20%
Gross Character:	Tan in color, no bedding present.
Texture:	Crystalline modified by solution.
Matrix and Cement:	Clay material as matrix, calcite grains cemented by calcite.
Fossils:	None

St. Peter Sandstone | Location: Pacific, Mo.

Mineral Composition:	Quartz............. 96% Calcite............ 4%
Gross Character:	Light color, massive bedding, friable.
Texture:	Average particle in coarse or massive sand grade, excellent sorting, well rounded grains, sphericity high, frosting.
Matrix and Cement:	Matrix lacking, cement minor, usually calcite however some silica cement is present.
Fossils:	None

CHAPTER III

DESCRIPTION OF EQUIPMENT AND EXPERIMENTAL PROCEDURE

Sonic Equipment

The sonic measurements were made using a Hewlett-Packard pulse generator as a driving mechanism, Clevite piezoelectric transducers as sending and receiving transducers, and a Tektronix oscilloscope as a time measuring device. A circuit diagram of the equipment is shown in Figure 2.

The Hewlett-Packard Model 214-A Pulse Generator is an instrument providing rectangular voltage pulses of variable amplitude and width at regularly spaced intervals of time. The pulse has a rise and fall time of less than 15 nanoseconds. The amplitude of the pulse can be varied from 80 millivolts to 100 volts. The pulse generator is capable of producing from 10 to 1,000,000 voltage pulses per second. The duration of these pulses can also be varied from 0.05 μ sec. to 10,000 μ sec. Figure 3 is a diagram showing the relationship between the pulse width and the repetition rate. A pulse width of 10 μ seconds and a repetition rate of 1000 cycles/sec was used for this research.

The Tektronix Model 502 oscilloscope is a dual beam scope. The vertical sensitivity ranges from 200 μ V/cm to 20 V/cm. The horizontal sweep range can be varied from 1

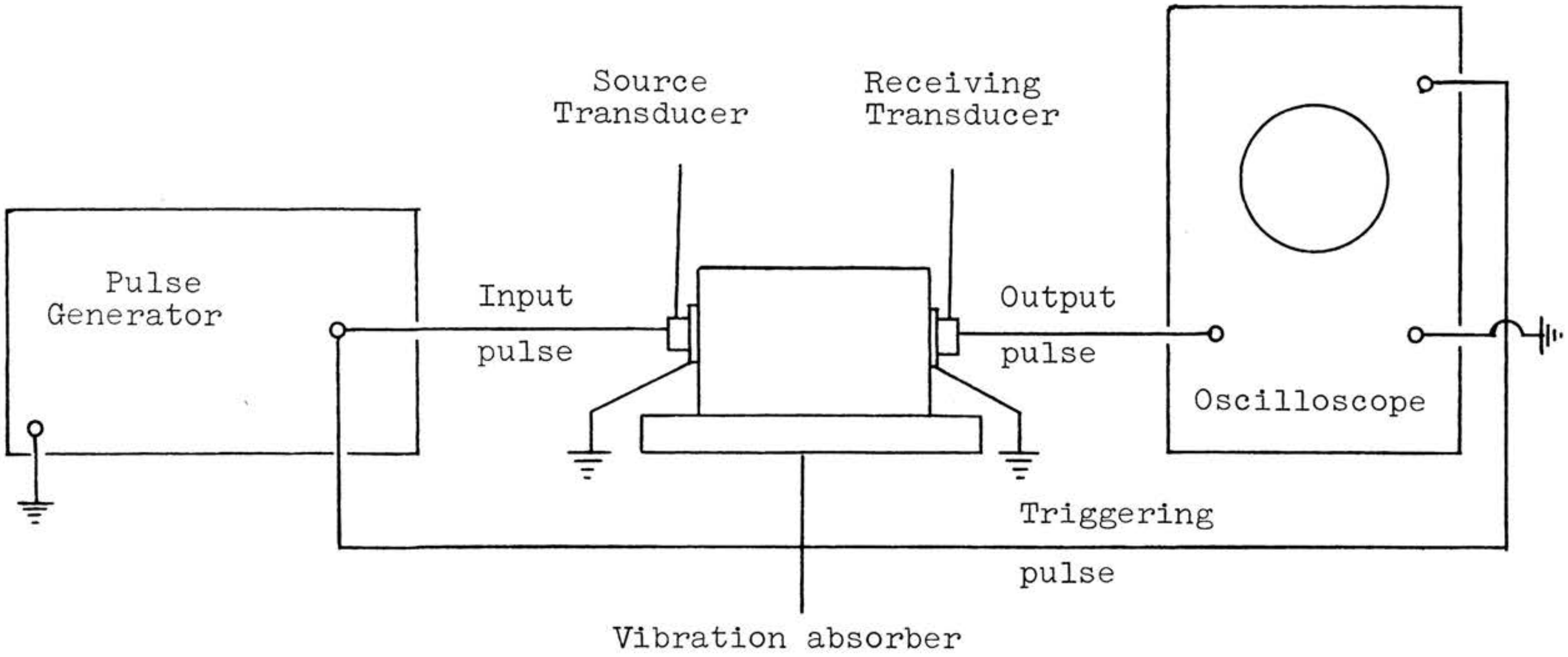


Figure 2. Circuit Diagram of Sonic Equipment

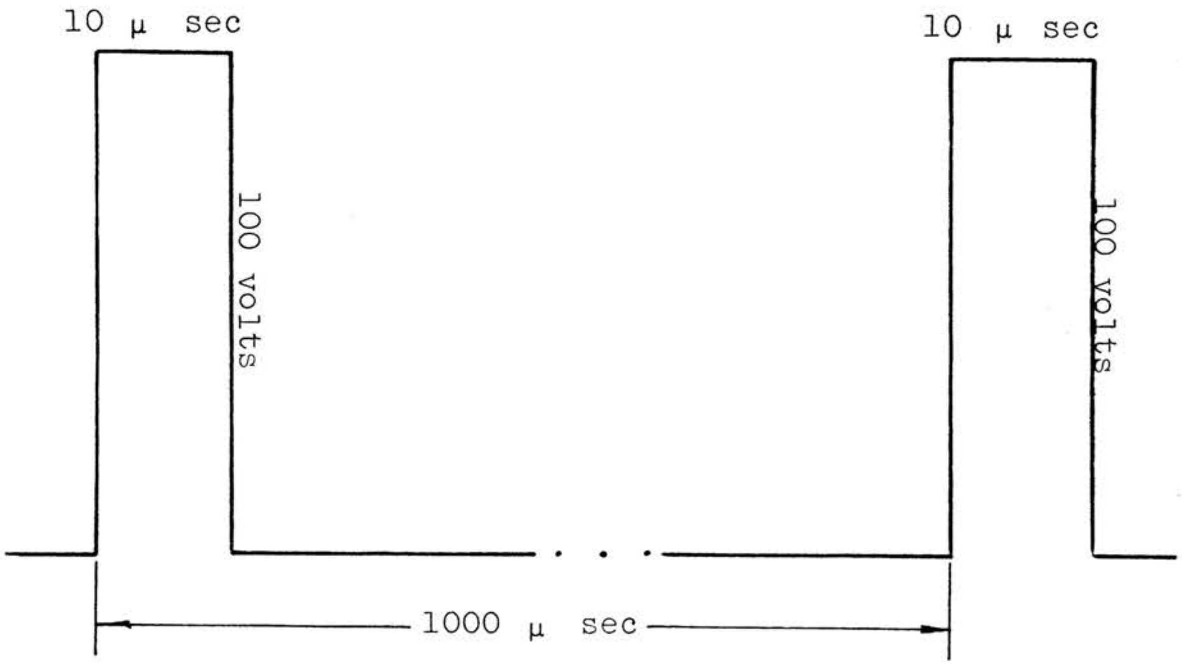


Figure 3. Input Pulse

μ sec/cm to 5 sec/cm and can be magnified X2, X5, X10, X20. The scope also has an amplitude calibrator with ranges from 0.5 millivolts to 5.0 volts.

Lead zirconate titanate, a piezoelectric ceramic, was used as sending and receiving transducers. This particular transducer material was chosen because of its high driving sensitivity, high efficiency in converting electrical energy into mechanical energy and vice-versa, high strain capacity, and its temperature stability. This ceramic is denoted as PZT-5 and can be obtained in a variety of sizes, shapes, and polarities from Clevite Electronic Components, 1915 North Harlem Avenue, Chicago 35, Illinois.

A special apparatus was designed to hold the piezoelectric transducers for longitudinal velocity measurements. Figure 4 is a mechanical drawing of the apparatus and Figure 5 is a photograph of the apparatus as it was used. The apparatus consists of seven parts. The following is a description of each part with their dimensions shown in Figure 4:

1. Housing: The housing is a steel cylinder machined so that each of the other parts can be held in their proper positions.
2. Piezoelectric transducer: This transducer is in the shape of a disc. The dimensions and tolerances of the disc, as supplied by the manufacturer, are as follows: diameter, 1.00 in. ± 0.015 in.; thickness,

0.270 in. ± 0.005 in.; surfaces are parallel within 0.005 in.; squareness is within 1.0 degree.

3. Brass disc: The purpose of the brass disc is to provide a good electrical contact with the back face of the transducer. The slender projection extending from the disc is to permit easy soldering of a lead wire.
4. Insulator: The insulator is made of Plexiglas. It is countersunk on each end. One end holds the brass disc in place while the other supports one end of the spring. The purpose of the insulator is to prevent electrical contact between the brass disc and the housing.
5. Spring: The spring constant was found by static calibration to be 110 lbs/in. The purpose of the spring is to apply pressure to the crystal.
6. Washer: The washer is made of steel and is countersunk so that it fits over the spring thereby holding it in place.
7. Adjusting screw: The adjusting screw is made of steel and has 11 threads per inch. Thus, one complete turn of the adjusting screw changes the force in the spring by 10 pounds.

The flanges on the housing of the jig support the steel plates which are used to clamp the jig to the specimen. Thumb screws are used to tighten the jig against the specimen. The screws are tightened until the jig is in firm contact

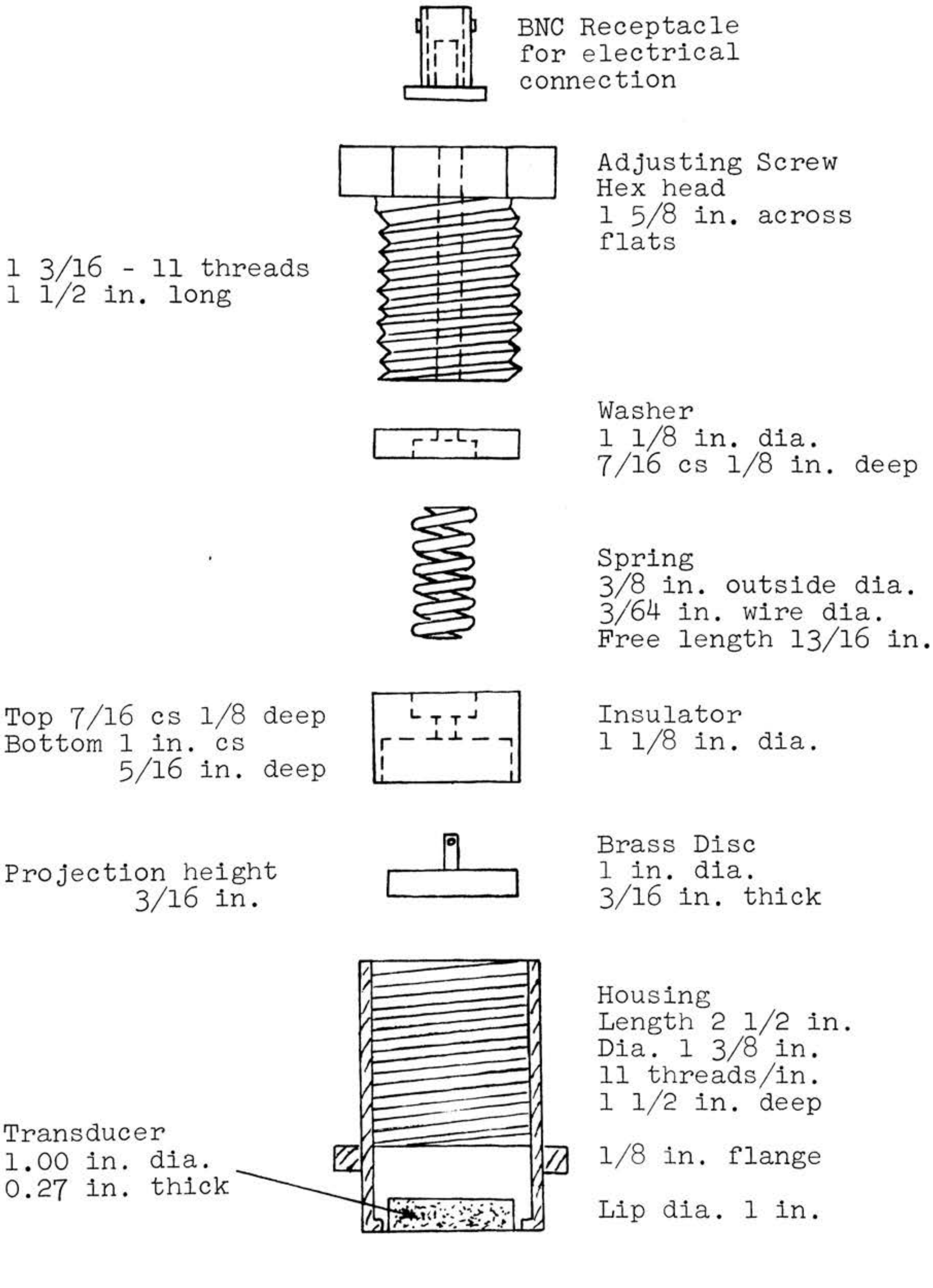


Figure 4. Mechanical Drawing of Jig

with The specimen. Figure 5 shows the assembly as it was used for testing.

Speciman Preparation

A simple procedure was followed in preparing the specimen for sonic measurement. Each specimen was cut into approximately 6 in. cubes. A 24 in. diamond saw manufactured by Highland Park Manufacturing Co., Pasadena, California was used for cutting the cubes. Because of the slow speed (585rpm) of the blade and the slow feed of the saw, the cut surfaces were smooth enough that very little additional surface preparation was needed. The specimens were allowed to dry approximately one week after cutting before the sonic tests were conducted. Longer periods of drying resulted in no significant changes in the wave velocities.

The length of travel was obtained within ± 0.005 in. by measuring each specimen on a surface table.

Measurement of the Longitudinal Wave Velocity

Each specimen was placed in the jig which has been previously described. A piece of aluminum foil was placed between the transducer and the specimen so that electrical contact was established between the outer surface of the transducer and the housing. The sending transducer was driven by the pulse generator with a pulse having an amplitude of 100 volts, a width or duration of 10 μ seconds, and a repetition rate of 1000 cycles per second. The output pulse from the pulse generator was also fed into the oscilloscope deflecting the upper beam. Figure 6 is a photograph of the input and the output wave as recorded on the oscilloscope.

The voltage output of the receiving transducer was fed into the lower beam of the oscilloscope as shown in Figure 6. The scope was triggered internally so that both sweeps started when the pulse was initiated. Because of attenuation the vertical gain of the lower beam had to be adjusted. Depending on the material the vertical gain used in measuring the P wave velocity ranged between 200 μ volts/cm and one volt/cm. Also depending on the material and the length of the specimen, the horizontal sweep time ranged between 5.0 μ sec/cm and 50.0 μsec/cm.

A considerable time was spent finding the optimum pressures which must be placed on the transducers for the best results. It was found that a 25 pound force on the sending transducer and a 15 pound force on the receiving transducer resulted in maximum voltage output from the receiving transducer. These forces were varied by turning the adjusting screw on the jig.

As an experimental check, the P wave velocities were also measured by gluing the transducers on the specimen with phenyl salicylate, a crystalline chemical which melts at 45°C. When this chemical is melted and allowed to recrystallize it exhibits excellent bonding properties. PZT-5 transducers having a diameter of 0.500 in. and a thickness of 0.250 in. were used. (Repeated tests proved this method to give the

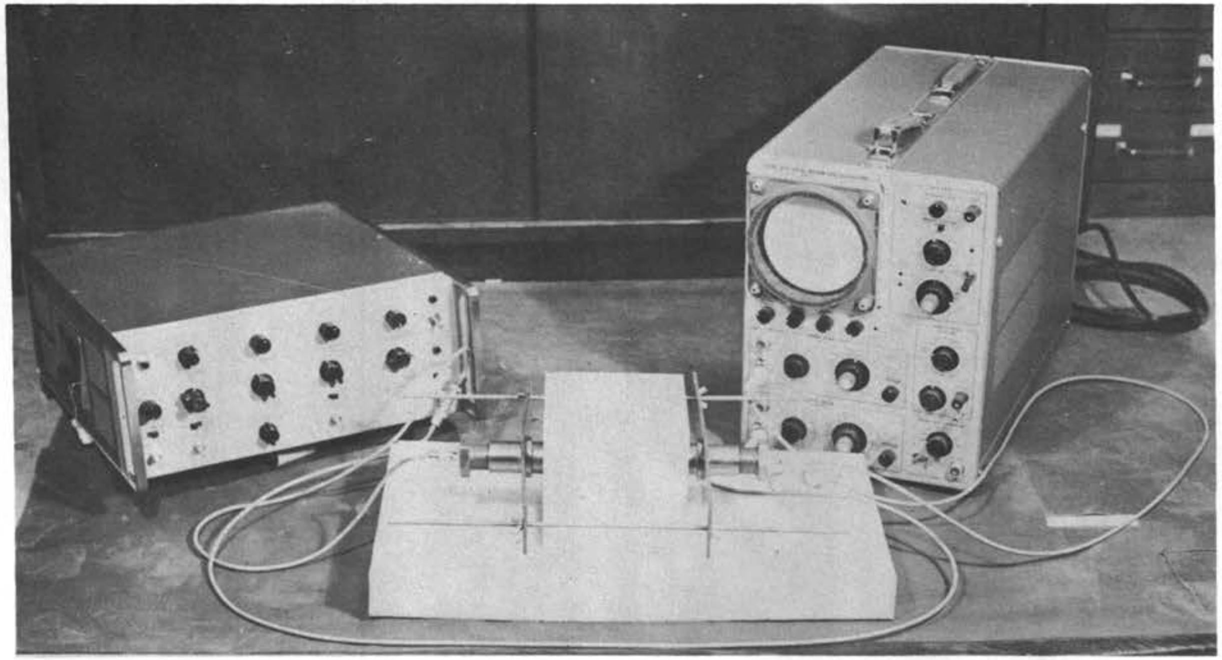
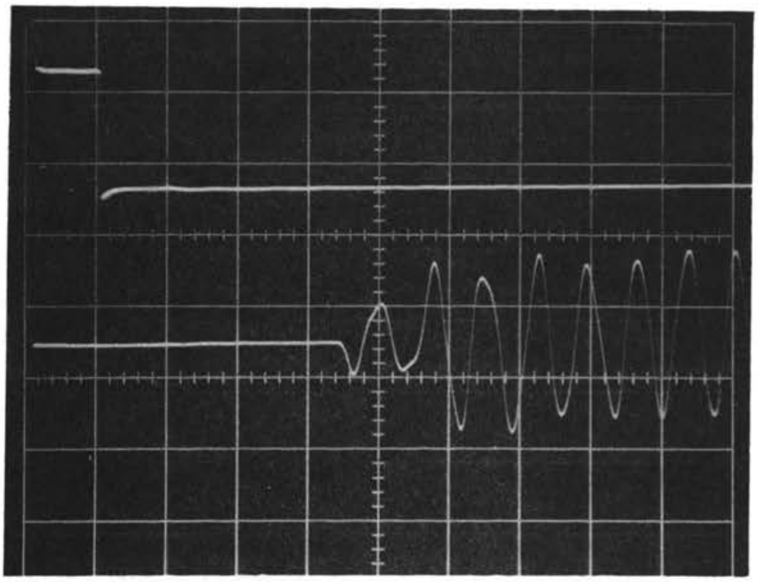


Figure 5. Apparatus for Measuring Sonic Velocities



Upper trace - Input pulse
Horizontal sweep time - 10 μ sec/cm
Vertical sensitivity - 20 v/cm

Lower trace - Output pulse
Horizontal sweep time - 10 μ sec/cm
Vertical sensitivity - 100 mv/cm

Figure 6. Input and Output Waveforms

best results in determining the longitudinal wave velocity). The travel times were the same with each method, however the attenuation was much less for the latter method as evidenced by a higher voltage output from the receiving transducer.

Electrical contact was maintained between the glued crystal and the specimen by painting the specimen with DuPont silver soldering paint (Order No. 4391-A). The paint provides a more intimate mechanical contact between the transducer and the rock surface than does either aluminum foil or graphite. Thus the transmission of the stress wave across the interface is improved.

Measurement of Shear Wave Velocities

The particle motion in a shear wave is perpendicular to the direction of propagation. Such a wave may be generated by: (1) use of shear transducers which generate shear waves directly; (2) using the principle that a longitudinal wave can be reflected as a pure shear wave; (3) utilizing the shearing action produced when a longitudinal transducer vibrates on a free surface.

Theoretically a pure shear wave can be generated from a transducer having axes of expansion and contraction perpendicular to the direction of electrical polarization. However first arrivals corresponding to P wave velocities were dominate. This indicated that the shear transducer generated both a shear wave and a longitudinal wave. Since the longitudinal velocity is approximately twice as fast as the shear velocity, any shear arrival was masked in the reverberations of the longitudinal wave.

Jamieson (3) describes a method of generating shear waves by a wedge technique. His method is based on the principle that any material having a Poisson's ratio less than 0.26 can be cut in such a manner so that a longitudinal wave impinging on a free face at the proper angle of incidence will be reflected as a pure shear wave. Figure 7 is a schematic diagram of this method. Pyrex is one material having a Poisson's ratio less than 0.26 and was used by Jamieson. Due to difficulty in obtaining the pyrex wedges this method was not used, however the author feels that the method would be excellent provided the impedence of the specimen and the wedge could be matched close enough to prevent too great an energy loss as the wave passes across the interface between the wedge and the medium.

The use of longitudinally polarized transducers as a method of generating shear waves was found most successful. Figure 8 is a schematic diagram of the setup. A strip of silver solder about 3/4 in. wide was painted along the center of one face of the specimen. This strip was then marked off in divisions of 1.00 $\pm$ 0.01 in. to facilitate accurate positioning of the 1/2 in. diameter longitudinal transducers. The source and receiving transducers were glued at each end of the silver strip and the travel time was measured on the oscilloscope. The source was then moved one inch closer to

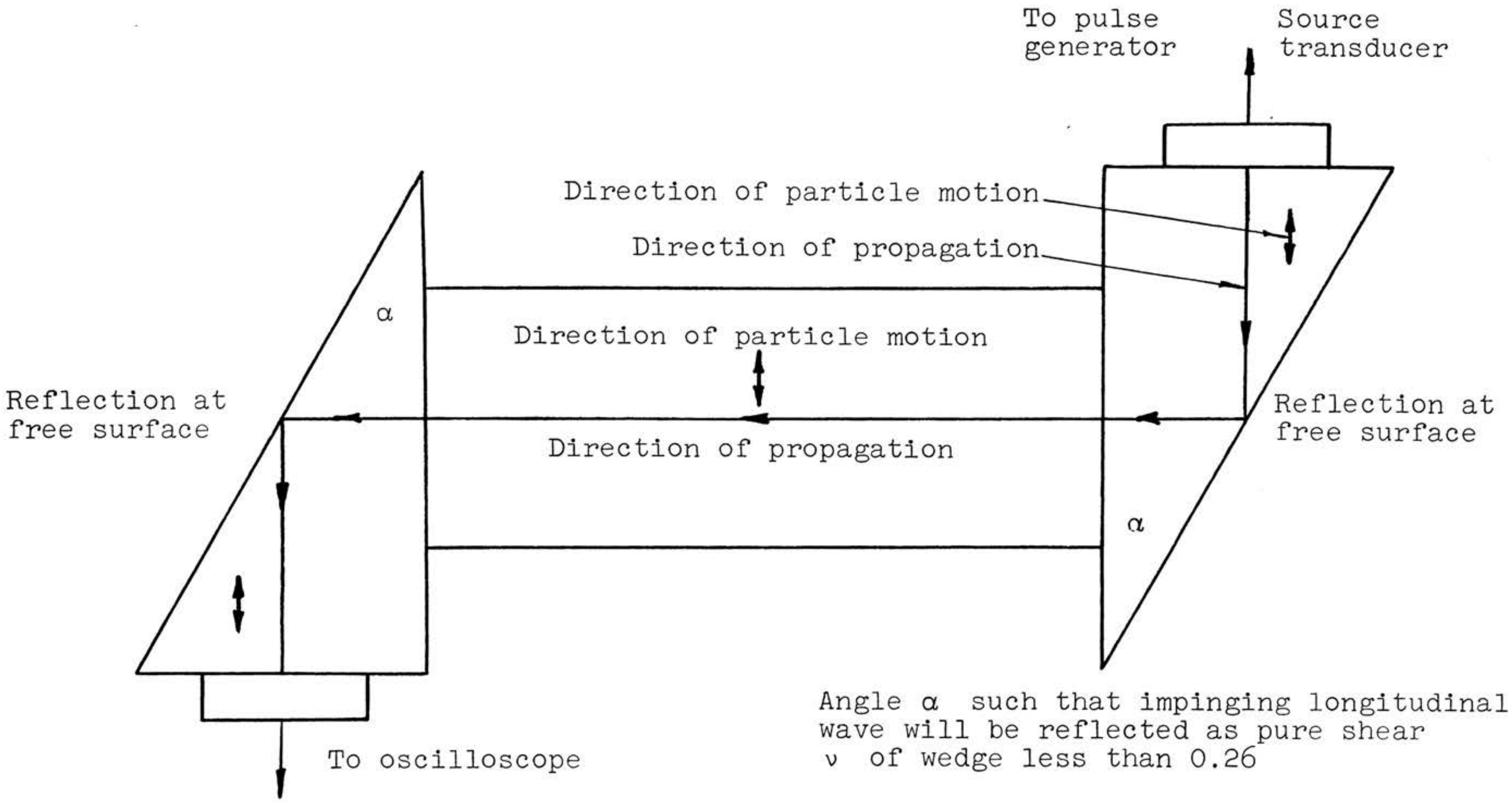


Figure 7 Jamieson's Wedge Technique for Generating Shear Waves

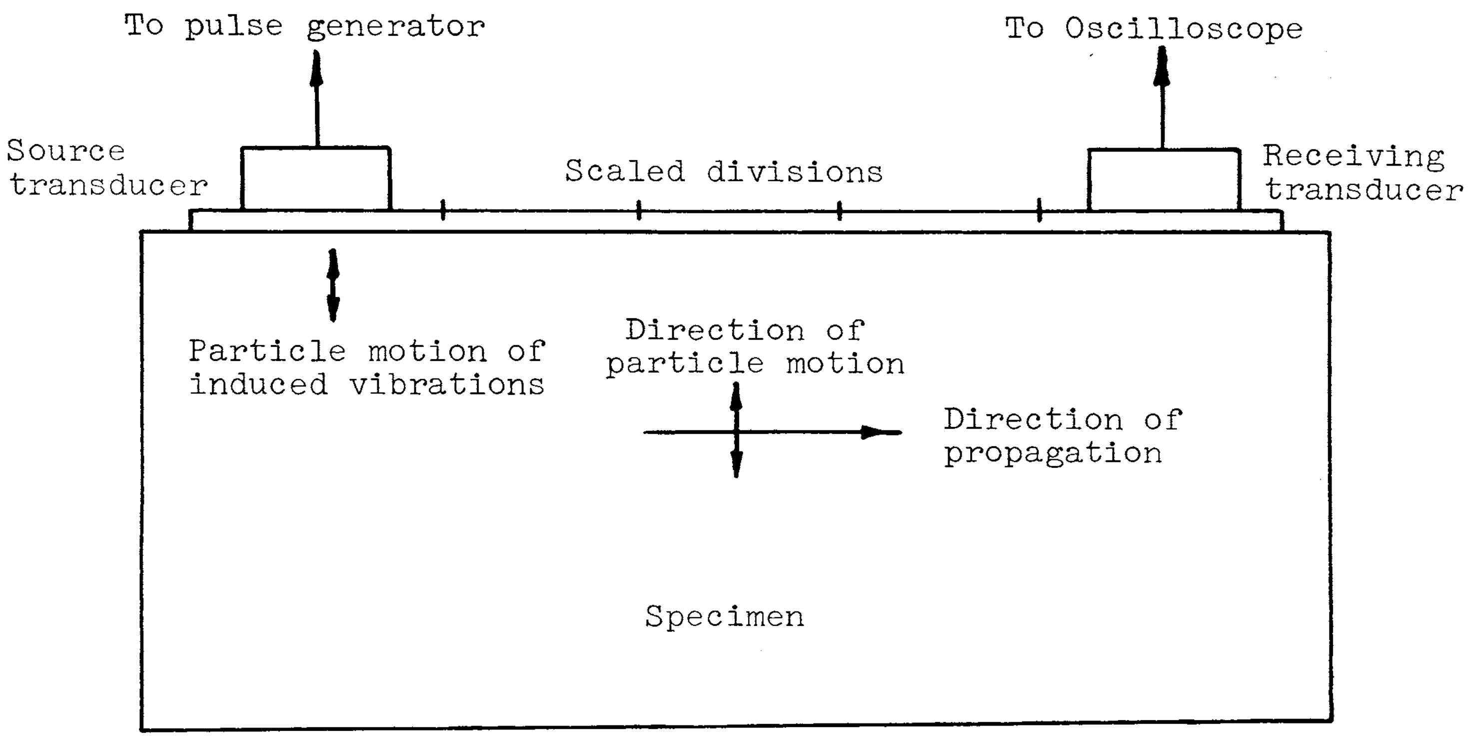


Figure 8. Shear Wave Generation Using Longitudinal Transducers

the receiver and the procedure was repeated. A time-distance curve was then plotted (see Figures 10 - 21), the slope of which was the shear velocity.

Static Equipment and Procedure

When the sonic measurements were completed, the rocks were then cored with a 1 3/4"inside diameter core bit. Baldwin SR-4 strain gages were mounted in principal directions. Each specimen was loaded in a 120,000 lb. Tinius Olsen testing machine and strain measurements were made using a Budd strain indicating device.

Baldwin SR-4, type A-7, paper back electrical resistance strain gages were used in this research. The gages were mounted using Eastman 910 adhesive. Mounting instructions can be found either with the gages or contained in the Eastman 910 package. The gages were obtained from Harris-Hansen Company, St. Louis, Missouri. The epoxy was obtained from Eastman Kodak Company, Kingsport, Tennessee.

The testing machine was operated on the 12,000 pound capacity range. The load pacer was adjusted so that a pressure of 100 psi/sec could be applied to the specimen. Depending on the material, a maximum force of either 4000 or 8000 pounds was placed on the specimen.

The strains were recorded on a Budd Strain indicator. The indicator is a portable model having an internal temperature compensating gage and direct digital tensile or compressive strain readings can be taken.

Considerable error in the strain measurements may be introduced due to friction between the platten and the end of a core loaded in compression. In order to eliminate this effect the cores were made approximately two diameters long and the gages were placed as close to the center of the core as possible. To further eliminate the effect of end restraint, each end of the core was covered with a viscous grease. The grease decreases the coefficient of friction between the rock and the platten. This allows the rock to expand freely in the lateral direction. As a substitute for the grease, two small rock cylinders were placed over each end of the core. The theory is that even though one end of the cylinders will be restrained, the cores will be able to expand freely. Figure 9 shows the various methods used to eliminate end restraint.

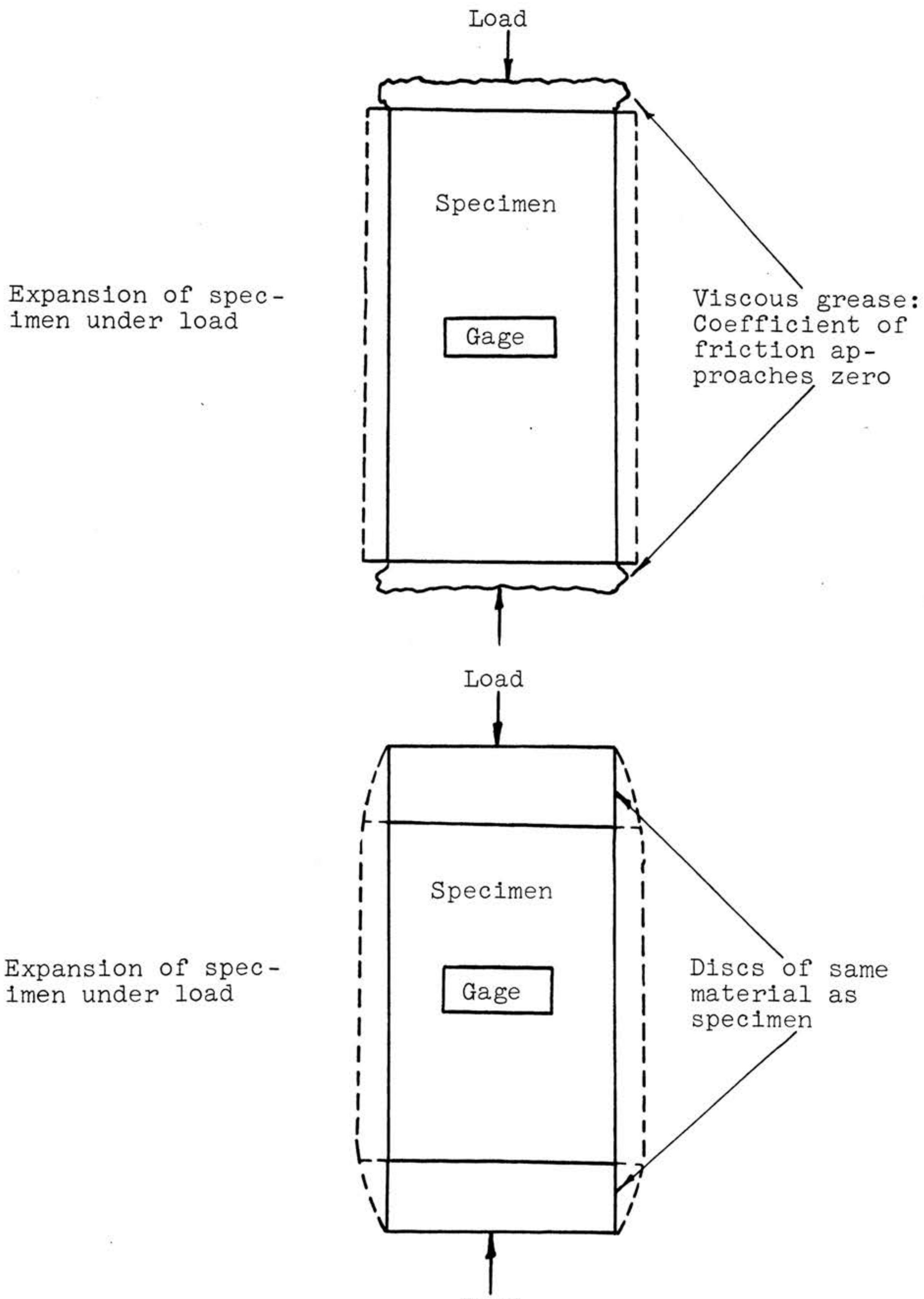


Figure 9 Methods Used to Eliminate End Restraint

CHAPTER IV

RESULTS OF TESTING

A wide variety of rock types were used in this research so that some sort of generalization could be made as to the validity of sonic testing as compared to static testing of various materials. The results of the research are given in this chapter.

The specimens are numbered, 1 through 12. The granite specimens are numbered 1, 2, and 3; the limestone specimens are numbered 4, 5, and 6; the sandstone specimens are numbered 7, 8, and 9; and the dolomite specimens are numbered 10, 11, and 12. The three major axes of each specimen are lettered X, Y, and Z.

Table I consists of the data that is needed to calculate the elastic constants by sonic methods. Table II consists of the calculated elastic constants obtained by both sonic and static methods and the percent deviation of the sonic values from the static values. Figures 10 - 21 show the time-distance curves for determining the shear velocity of each specimen. Figures 22-31 show the static stress-strain curves for each specimen.

A discussion of the results presented in this chapter will be given in Chapter V.

TABLE I

SONIC DATA

Rock Type	Specimen No.	Density (lb/ft^3)	V_L (ft/sec)	V_S (ft/sec)
Georgia Granite	1-X	165.56	13270	7200
Georgia Granite	1-Y	165.56	10000	7400
Georgia Granite	1-Z	165.56	13200	7600
Georgia Granite	2-X	165.56	10000	7400
Georgia Granite	2-Y	165.56	13200	7900
Georgia Granite	2-Z	165.56	14100	7400
Georgia Granite	3-X	165.56	10900	7400
Georgia Granite	3-Y	165.56	13900	7400
Georgia Granite	3-Z	165-56	14100	8000
Platten LS	4-X	161.66	18700	9000
Platten LS	4-Y	161.66	17700	9900
Platten LS	4-Z	161.66	17800	9800
Platten LS	5-X	161.66	16800	8500
Platten LS	5-Y	161.66	16700	8500
Platten LS	5-Z	161.66	16800	7200
Platten LS	6-X	161.66	15300	8300
Platten LS	6-Y	161.66	13800	8100
Platten LS	6-Z	161.66	17600	9300
St. Peter SS	7-X	150.78	4900	4100
St. Peter SS	7-Y	150.78	5500	3500
St. Peter SS	7-Z	150.78	4800	2800

TABLE I

SONIC DATA (continued)

Rock Type	Specimen No.	Density (lb/ft^3)	V_L (ft/sec)	V_S (ft/sec)
St. Peter SS	8-X	150.78	8900	5700
St. Peter SS	8-Y	150.78	8700	6100
St. Peter SS	8-Z	150.78	6800	6200
St. Peter SS	9-X	150.78	6300	4100
St. Peter SS	9-Y	150.78	8500	4700
St. Peter SS	9-Z	150.78	6700	4100
Jeff City Dolo	10-X ✓	159.66	15200	8300
Jeff City Dolo	10-Y	159.66	14500	8300
Jeff City Dolo	10-Z	159.66	15300	9300
Jeff City Dolo	11-X ✓	159.66	14600	8300
Jeff City Dolo	11-Y	159.66	13000	7500
Jeff City Dolo	11-Z	159.66	17800	8300
Jeff City Dolo	12-X ✓	159.66	16000	8300
Jeff City Dolo	12-Y	159.66	13600	7600
Jeff City Dolo	12-Z	159.66	13900	6700

TABLE II

ELASTIC CONSTANTS AND % DEVIATION

Specimen No.	E Sonic 10^6 psi	E Static 10^6 psi	% Dev.	ν (sonic)	ν (static)	% Dev.	μ Sonic 10^6 psi	μ Static 10^6 psi	%Dev.
1-X	4.78	5.10	6.27	0.291	0.079	268.3	1.85	2.36	21.60
1-Y	3.50	3.85	9.09	-0.105	0.063	66.7	1.96	1.81	8.28
1-Z	5.16	6.66	22.50	0.252	0.216	16.6	2.06	2.74	24.60
2-X	3.50	4.04	13.40	-0.140	0.140	25.0	1.96	1.77	10.70
2-Y	5.44	4.68	16.20	0.221	0.076	190.8	2.23	1.92	16.10
2-Z	5.12	6.66	23.10	0.310	0.175	77.1	1.96	2.83	30.70
3-X	4.19	4.86	14.30	0.078	0.171	54.4	1.94	2.09	7.20
3-Y	5.09	3.54	43.80	0.302	0.106	184.9	1.96	1.60	22.50
3-Z	5.77	6.56	12.00	0.263	0.151	74.2	2.28	2.85	20.00
4-X	7.62	7.41	2.80	0.349	0.302	15.6	2.82	2.84	1.00
4-Y	8.70	8.00	8.75	0.272	0.200	36.0	3.42	3.33	2.70
4-Z	8.59	7.14	20.30	0.282	0.259	8.9	3.35	2.84	17.90

TABLE II (continued)

ELASTIC CONSTANTS AND % DEVIATION

Specimen No.	E Sonic 10^6 psi	E Static 10^6 psi	% Dev.	ν(sonic)	ν(static)	% Dev.	μ Sonic 10^6 psi	μ Static 10^6 psi	% Dev.
5-X	6.43	9.41	31.70	0.339	0.259	31.7	2.40	3.74	35.80
5-Y	6.68	8.16	18.10	0.325	0.235	38.3	2.52	3.30	23.60
5-Z	5.02	9.76	48.60	0.390	0.361	8.0	1.81	3.58	49.40
6-X	6.20	10.95	43.40	0.291	0.424	31.4	2.40	3.84	37.50
6-Y	5.66	13.56	58.30	0.237	0.399	30.1	2.29	5.06	54.70
6-Z	7.89	No Data	----	0.306	No Data	----	3.02	No Data	-----
7-X	3.64	No Data	----	-0.667	No Data	----	5.47	No Data	-----
7-Y	9.24	No Data	----	0.160	No Data	----	3.98	No Data	-----
7-Z	6.33	No Data	----	0.242	No Data	----	2.55	No Data	-----
8-X	2.43	2.70	10.00	0.152	0.216	20.6	1.06	1.11	4.50
8-Y	2.46	2.82	12.80	0.017	0.239	92.9	1.21	1.14	6.10
8-Z	2.41	No Data	----	1.964	No Data	----	1.25	No Data	-----

TABLE II (continued)

ELASTIC CONSTANTS AND % DEVIATION

Specimen No.	E Sonic 10^6 psi	E Static 10^6 psi	% Dev.	ν (sonic)	ν (static)	% Dev.	μ Sonic 10^6 psi	μ Static 10^6 psi	% Dev.
9-X	1.24	No Data	-----	0.133	No Data	----	5.47	No Data	----
9-Y	1.84	No Data	-----	0.280	No Data	----	7.18	No Data	----
9-Z	1.31	No Data	-----	0.301	No Data	----	5.47	No Data	----
10-X	6.11	4.30	42.10	0.288	0.305	5.6	2.37	2.34	0.10
10-Y	5.96	5.29	12.70	0.256	0.317	19.2	2.37	2.26	4.80
10-Z	7.19	5.88	22.30	0.207	0.265	21.9	2.98	2.84	4.90
11-X	5.98	No Data	-----	0.261	No Data	----	2.37	No Data	----
11-Y	4.84	No Data	-----	0.251	No Data	----	1.94	No Data	----
11-Z	11.43	6.46	43.50	0.361	0.686	47.4	2.37	1.92	23.40
12-X	6.24	5.00	24.80	0.316	0.350	9.7	2.37	2.31	2.60
12-Y	5.06	7.14	29.10	0.273	0.379	28.0	1.99	1.83	8.70
12-Z	4.17	4.30	3.02	0.349	0.172	102.9	1.54	1.78	13.50

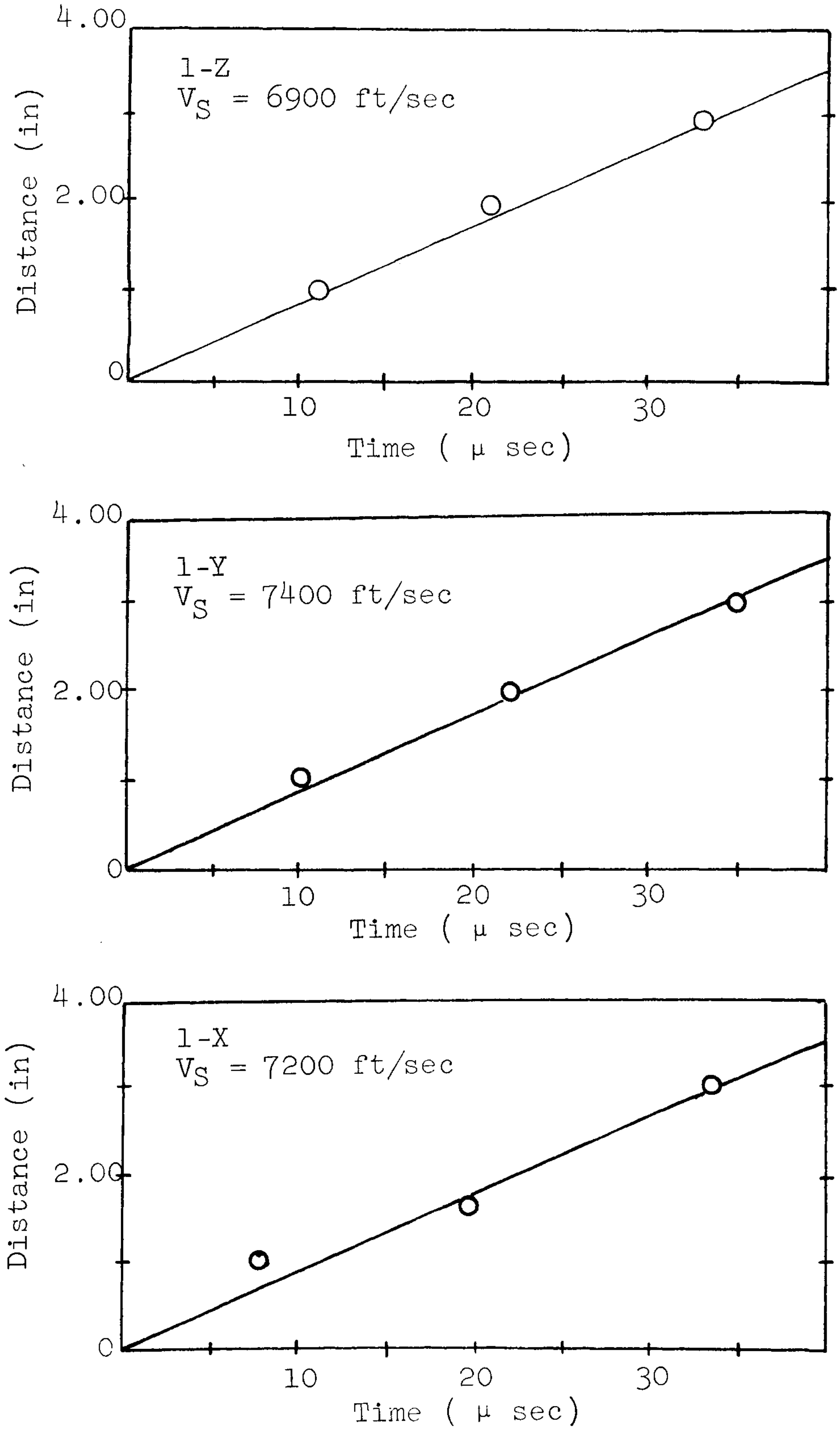


Figure 10. Georgia Granite Specimen No. 1

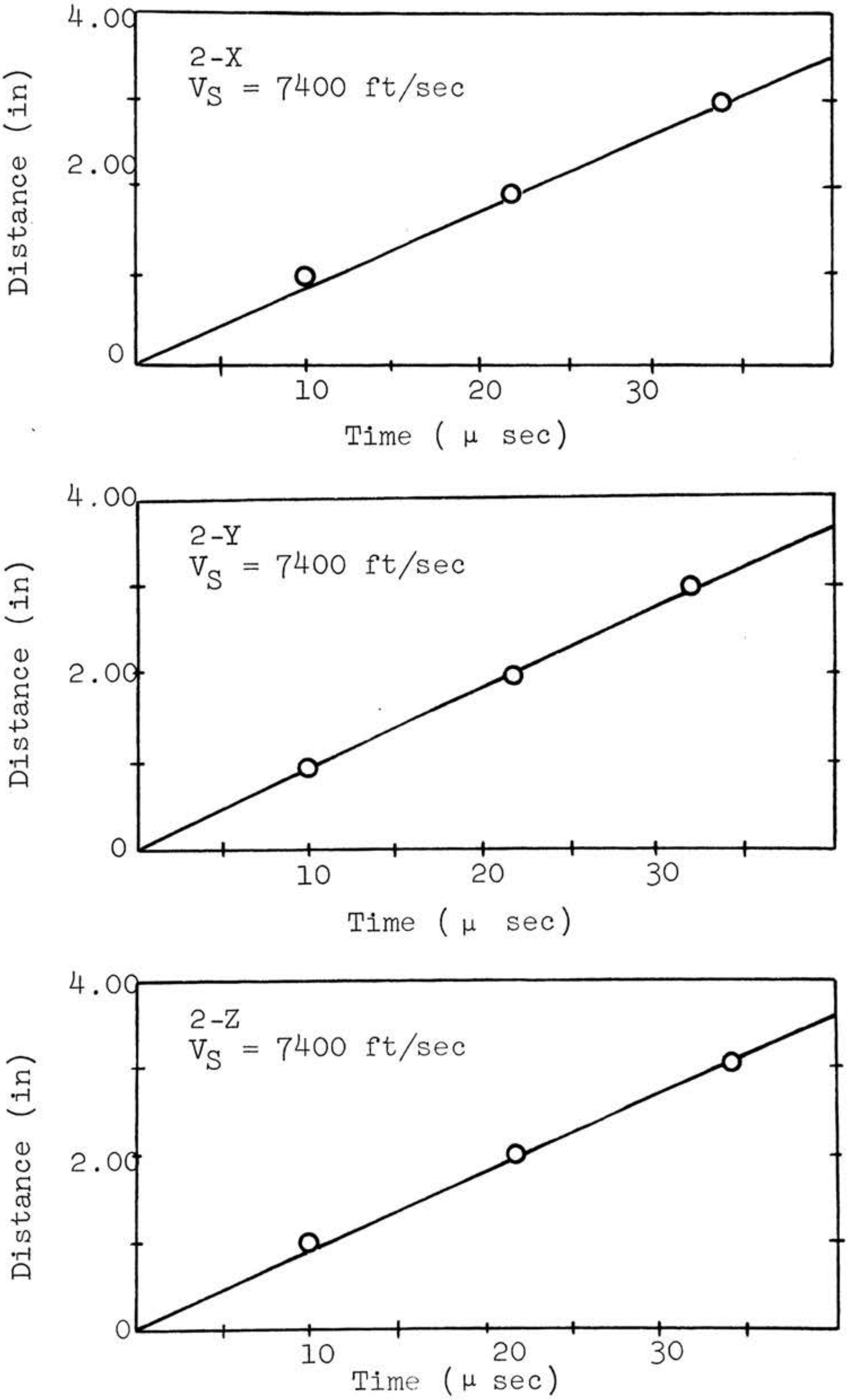


Figure 11. Georgia Granite Specimen No. 2

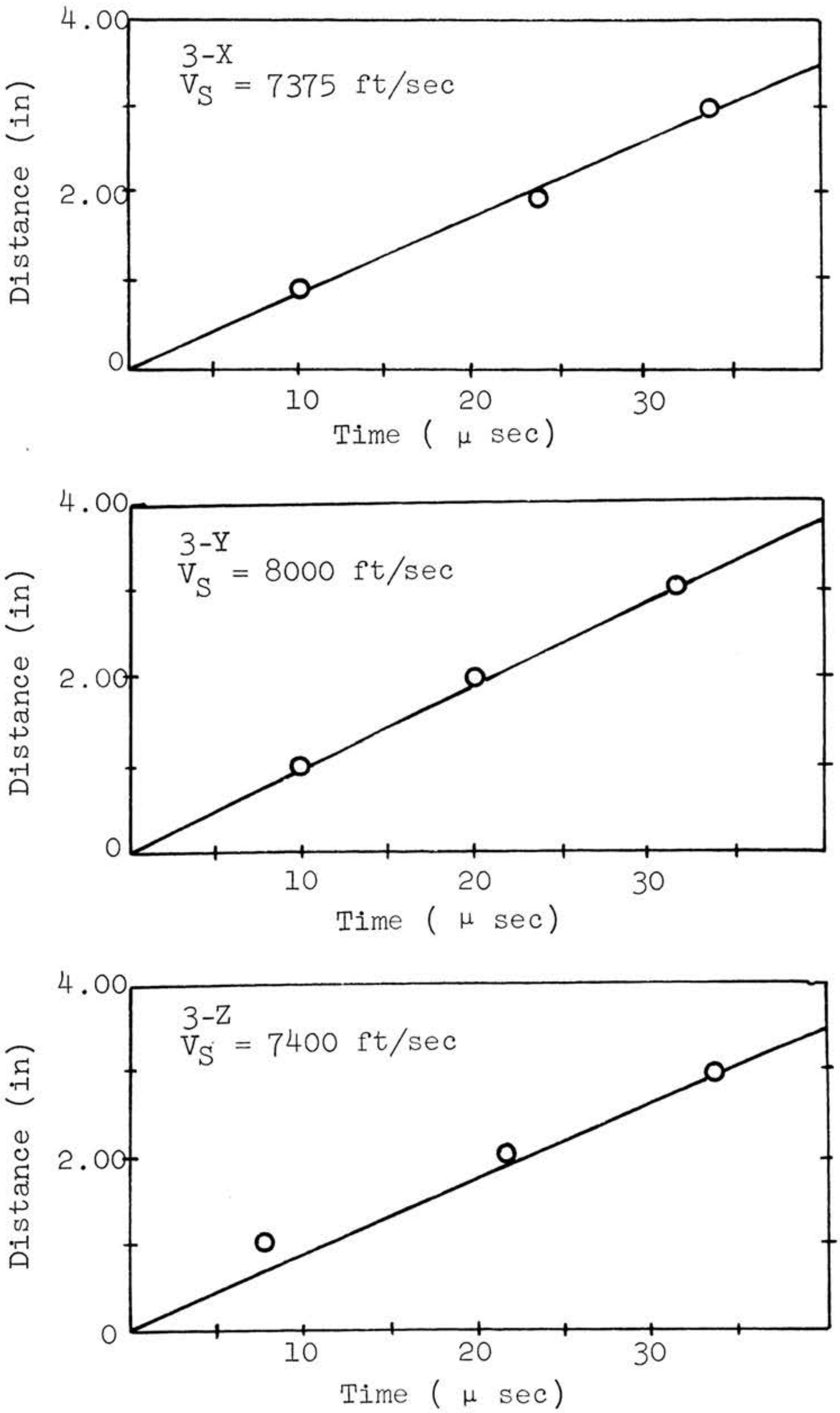


Figure 12 Georgia Granite Specimen No. 3

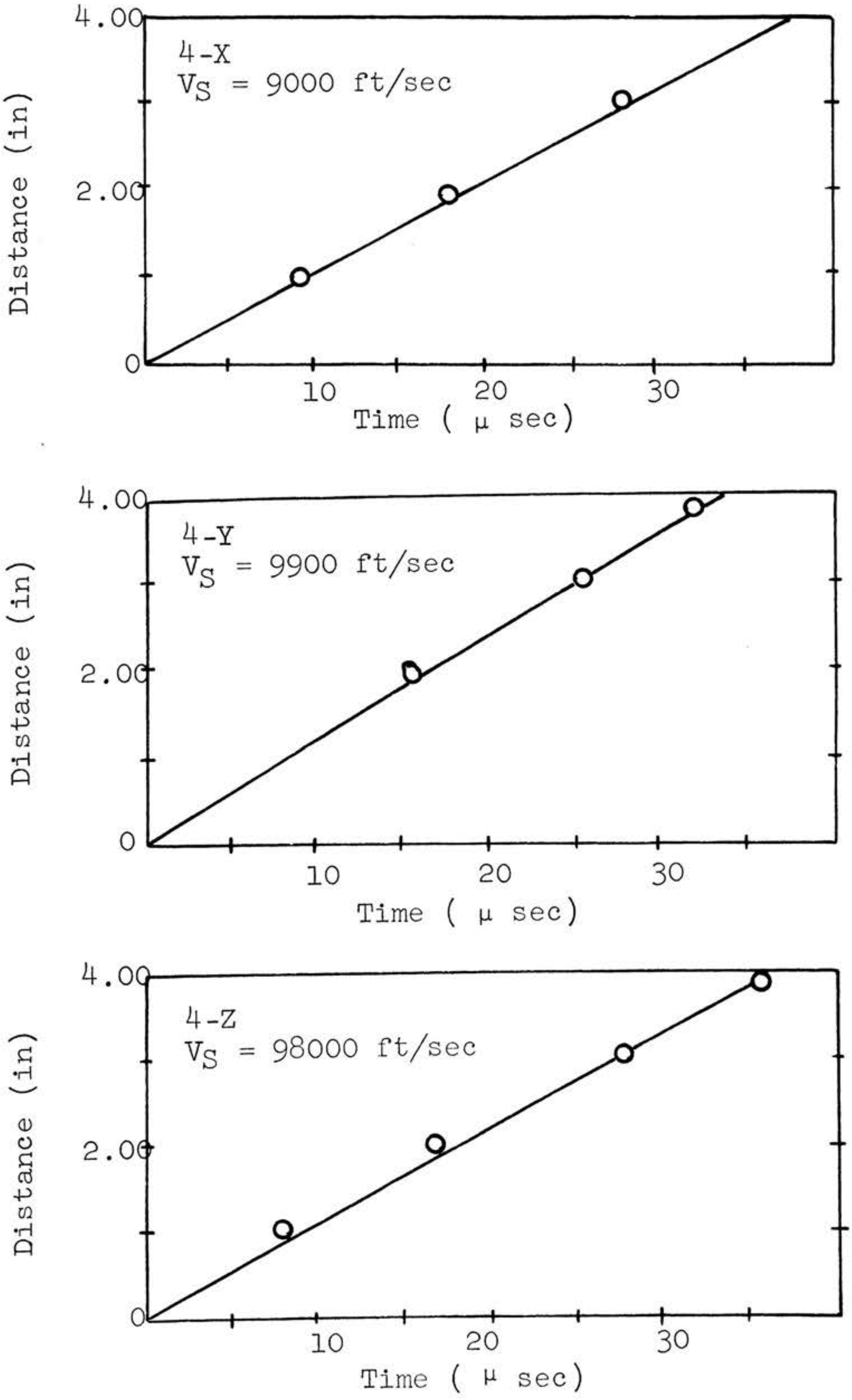


Figure 13. Platten Limestone Specimen No. 4

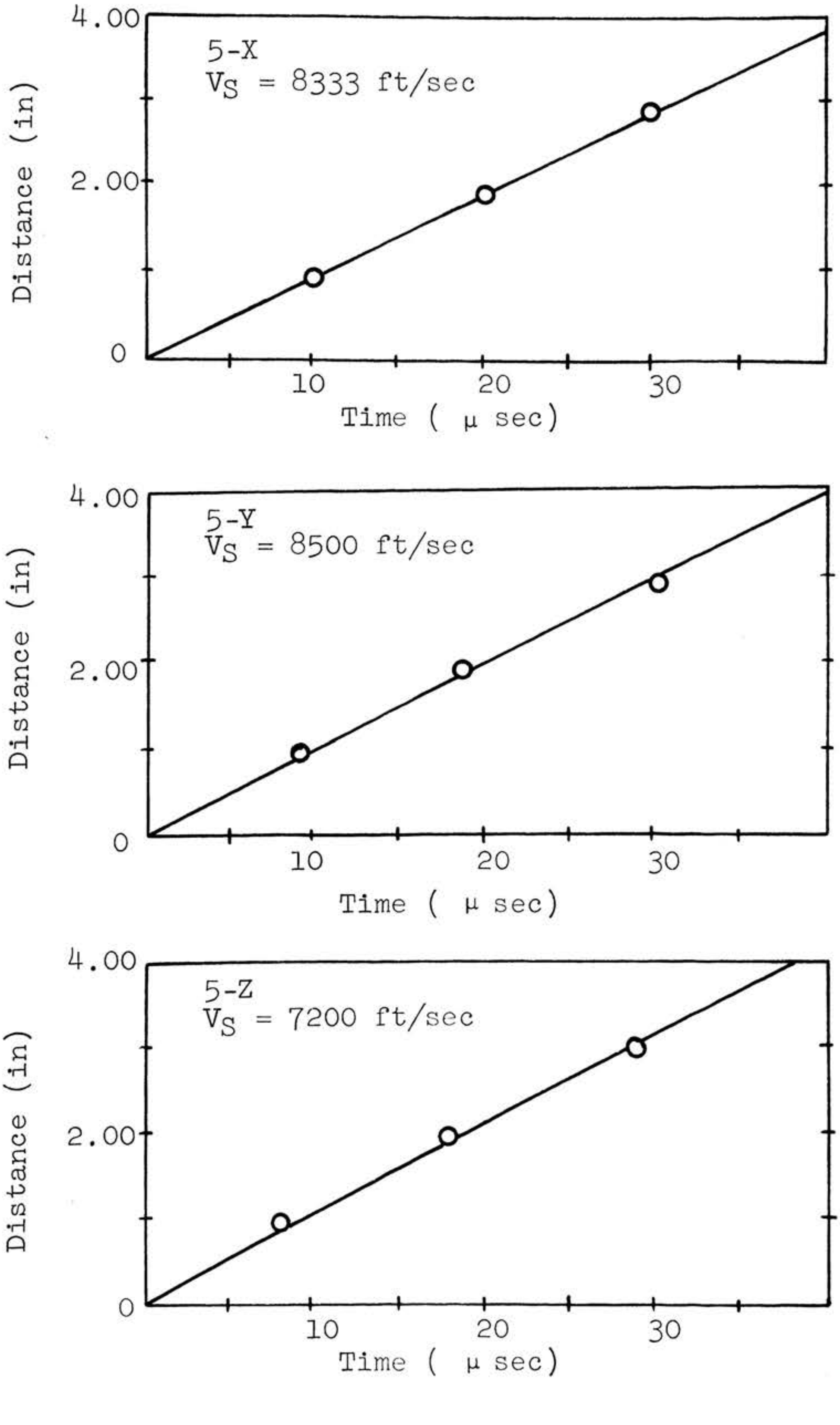


Figure 14. Platten Limestone Specimen No. 5

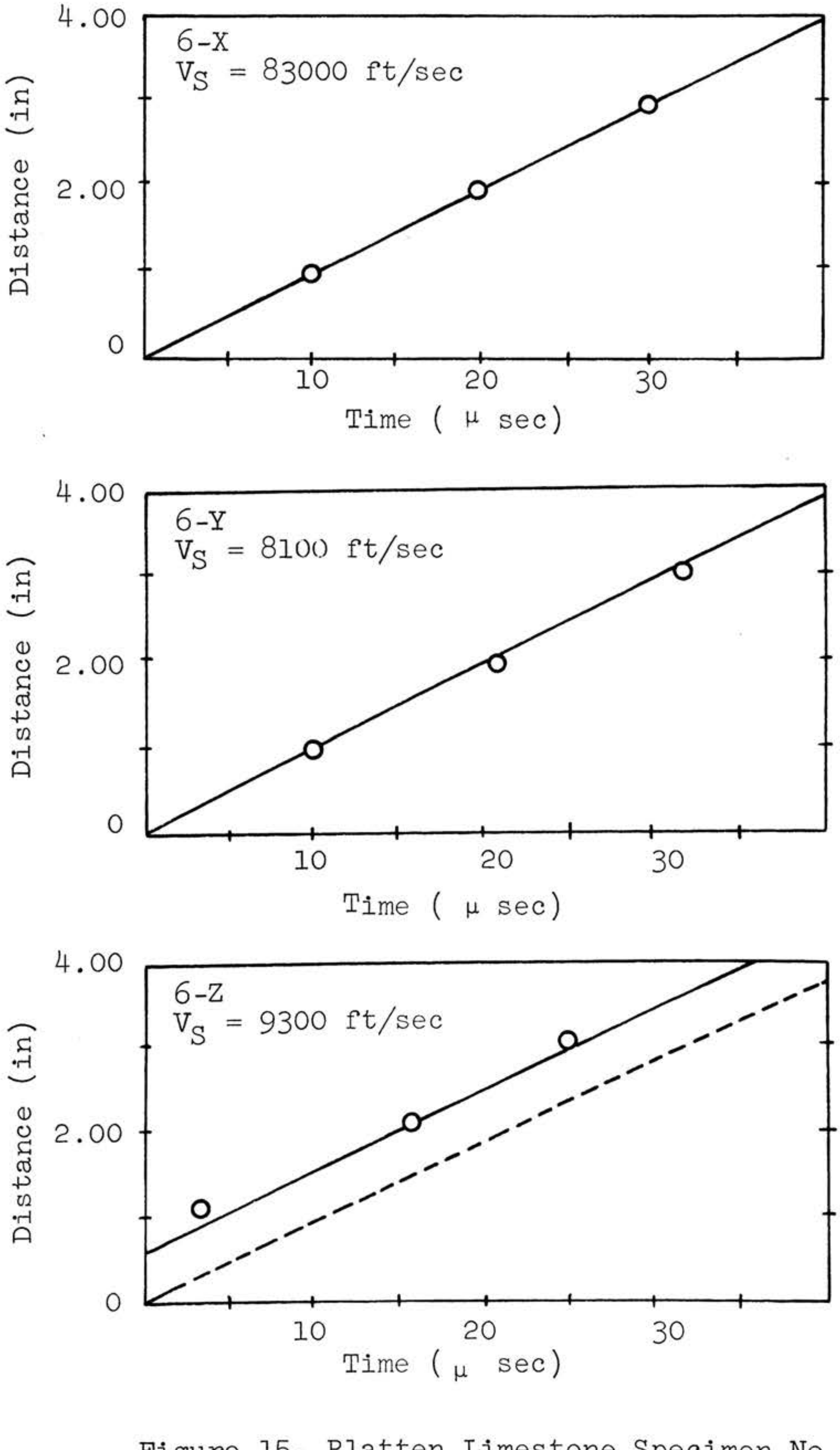


Figure 15. Platten Limestone Specimen No. 6

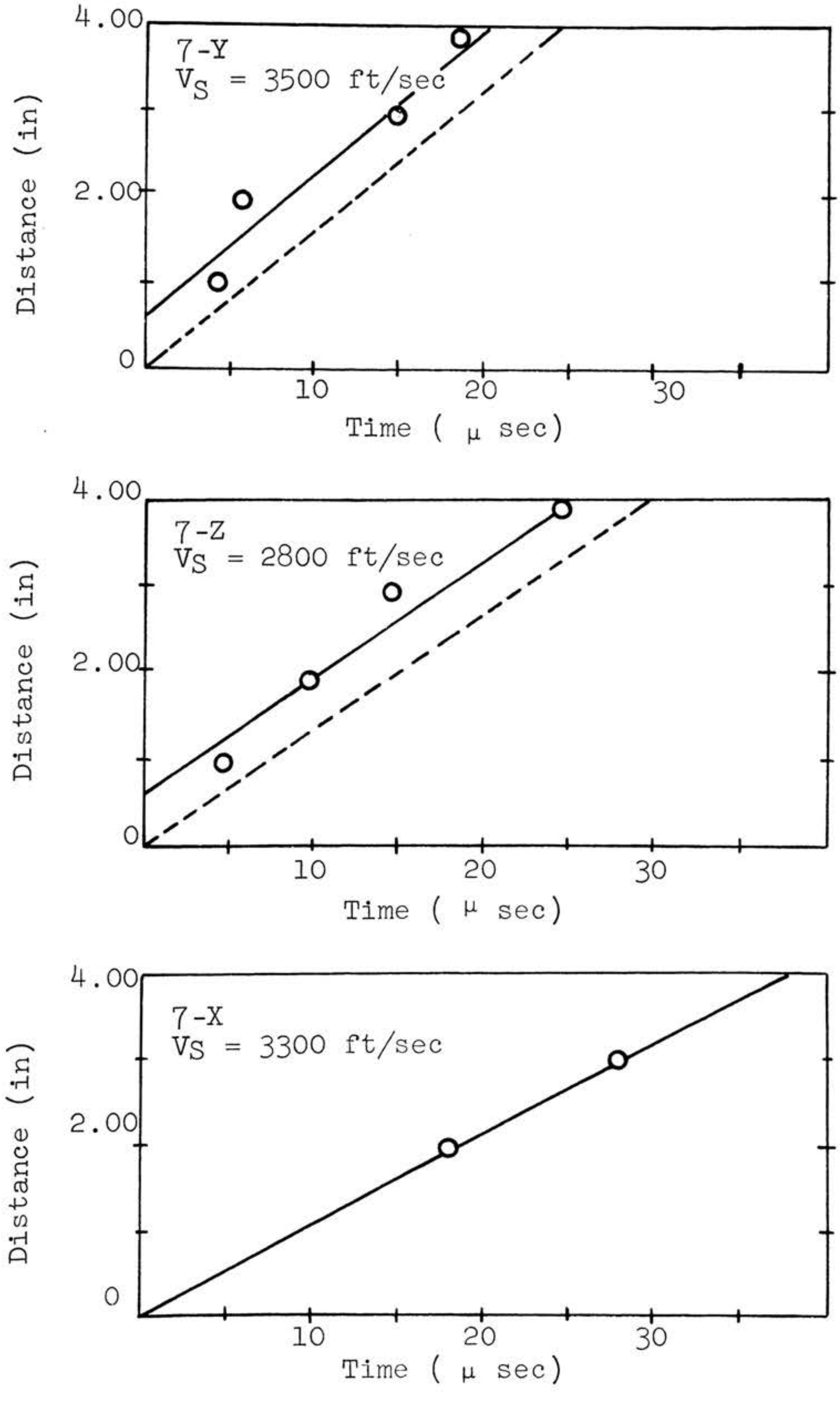


Figure 16. St. Peter Sandstone Specimen No. 7

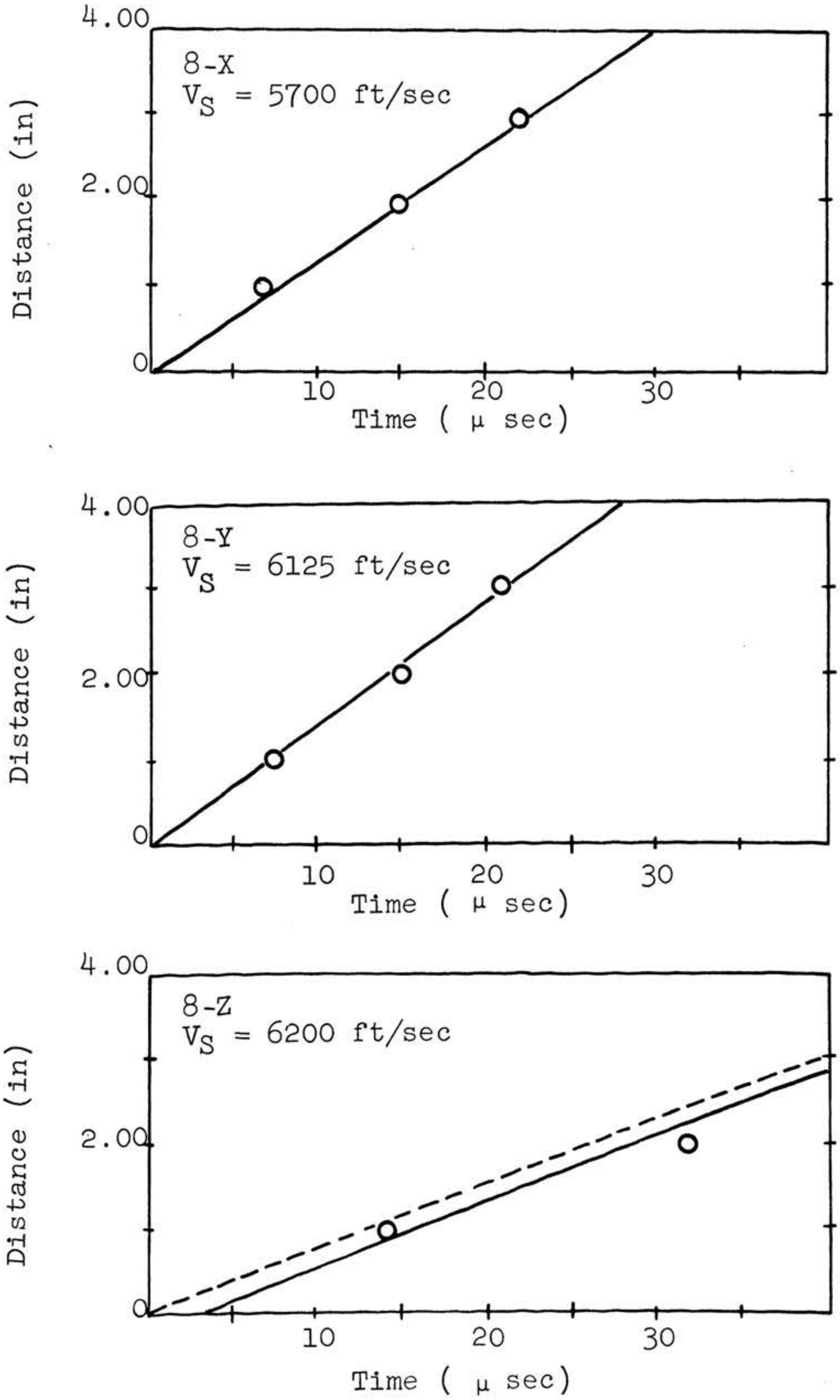


Figure 17. St. Peter Sandstone Specimen No. 8

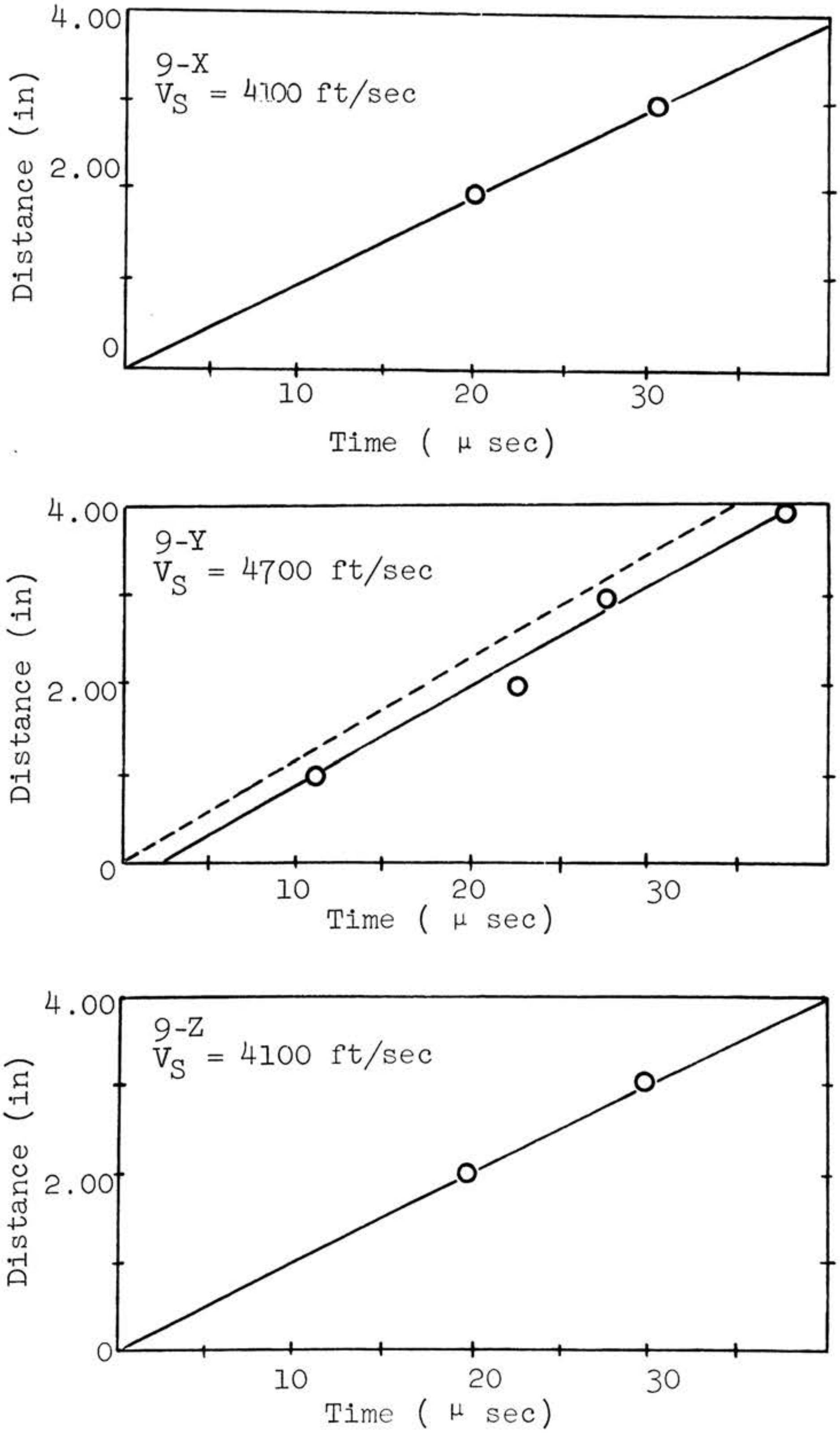


Figure 18. St. Peter Sandstone Specimen No. 9

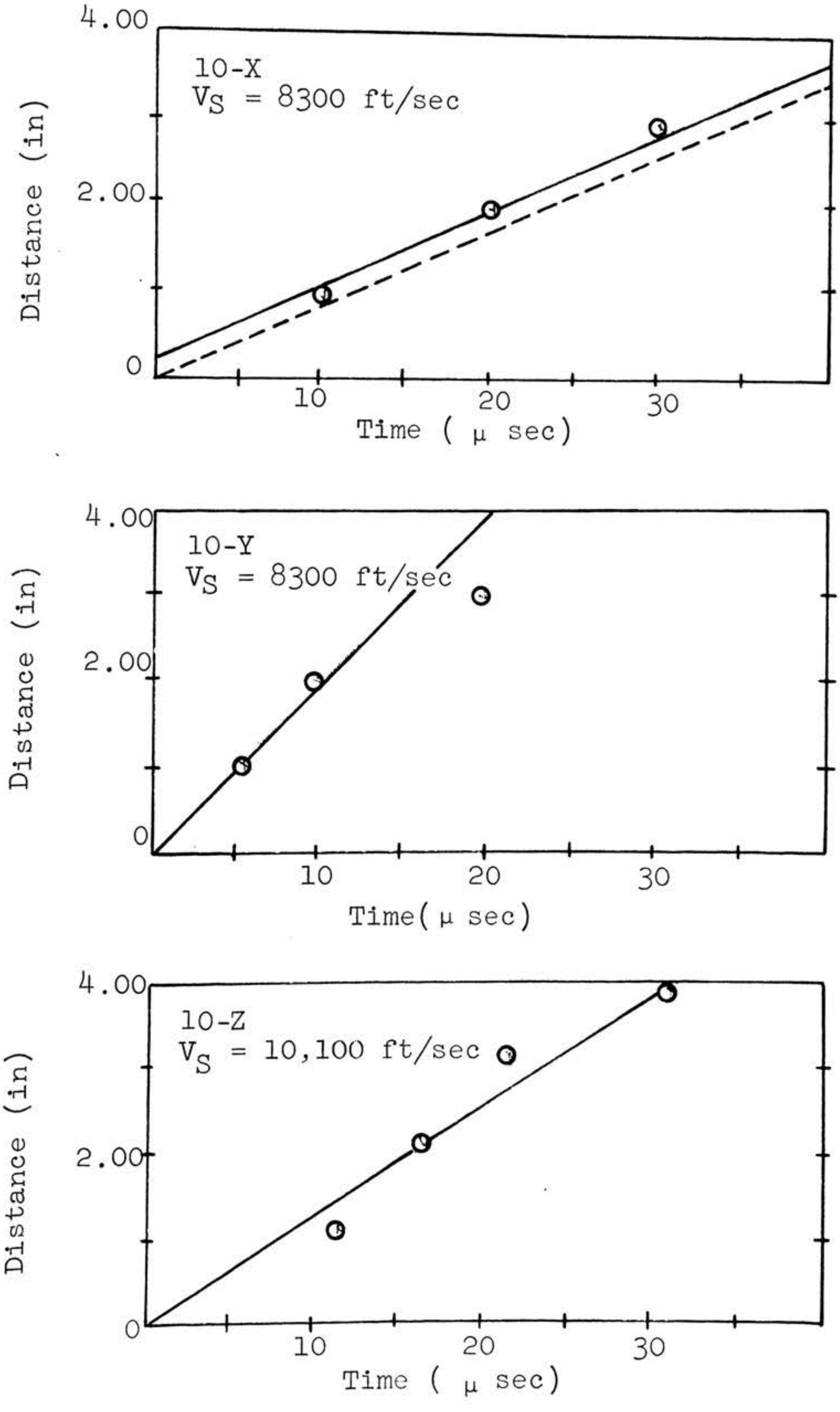


Figure 19. Jefferson City Dolomite Specimen No. 10

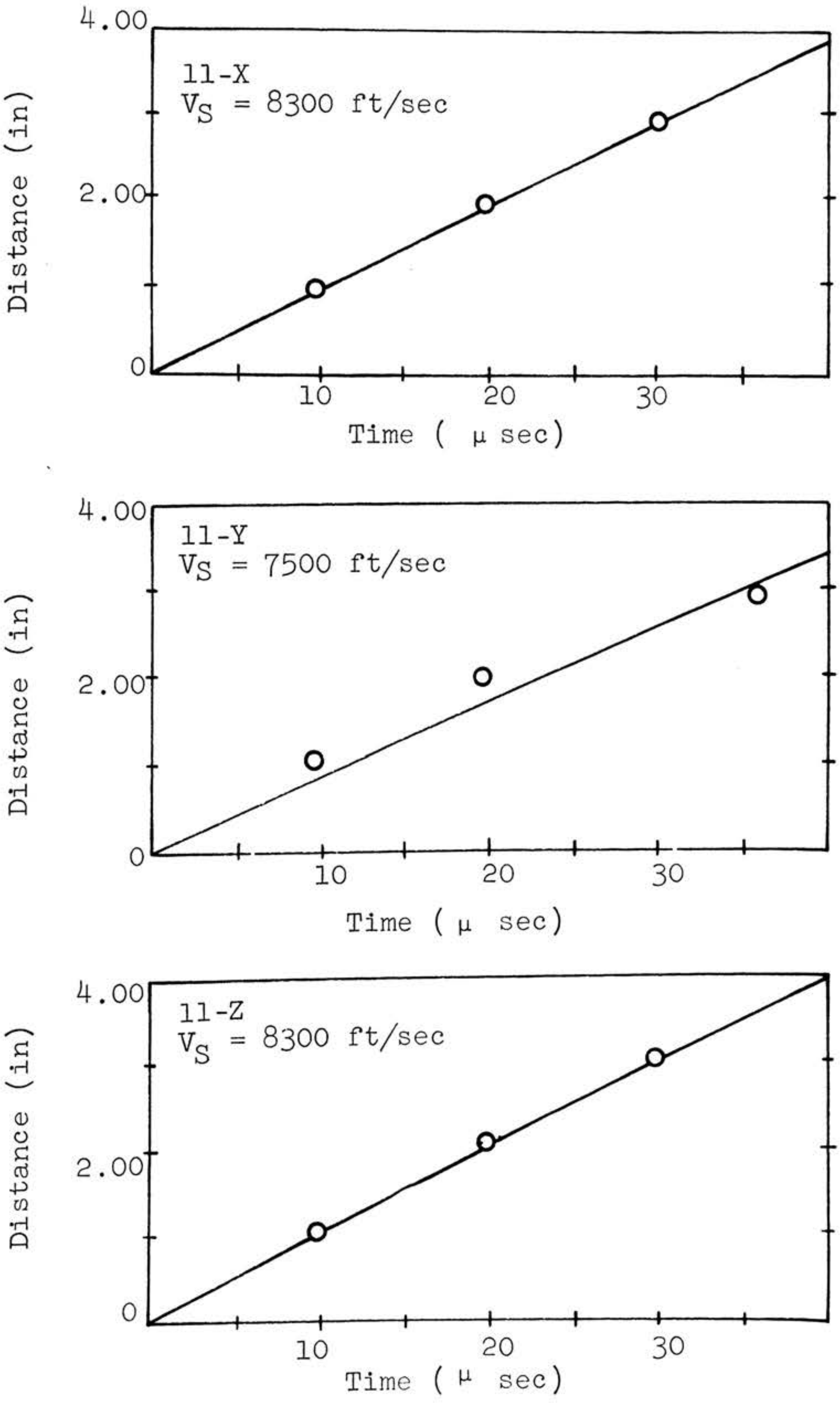


Figure 20 Jefferson City Dolomite Specimen No. 11

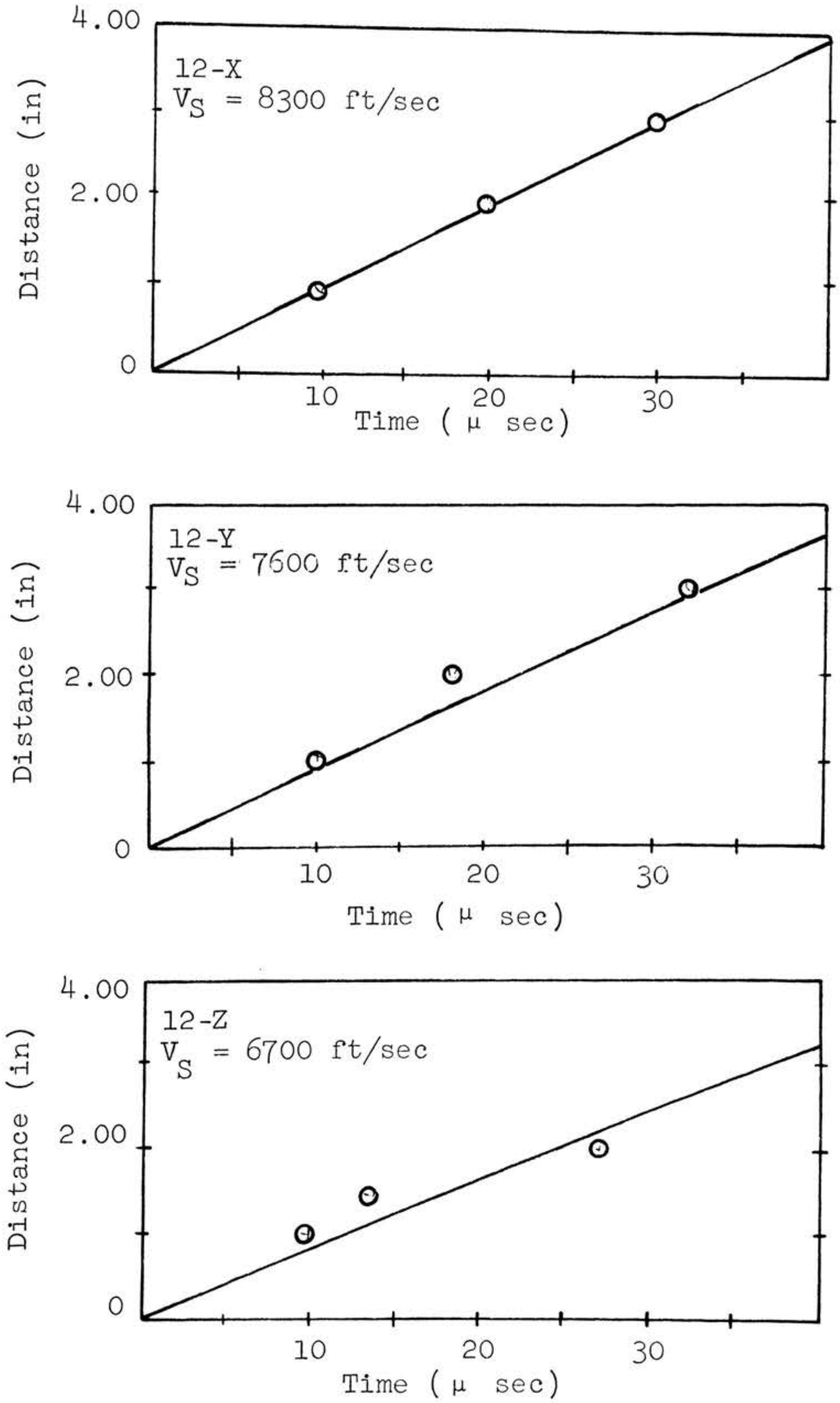


Figure 21. Jefferson City Dolomite Specimen No. 12

Explanation of Stress-Strain Curves

o longitudinal strain values

△ lateral strain values

Dashed line is a correction line through the origin drawn parallel to best straight line (solid) through the experimental points.

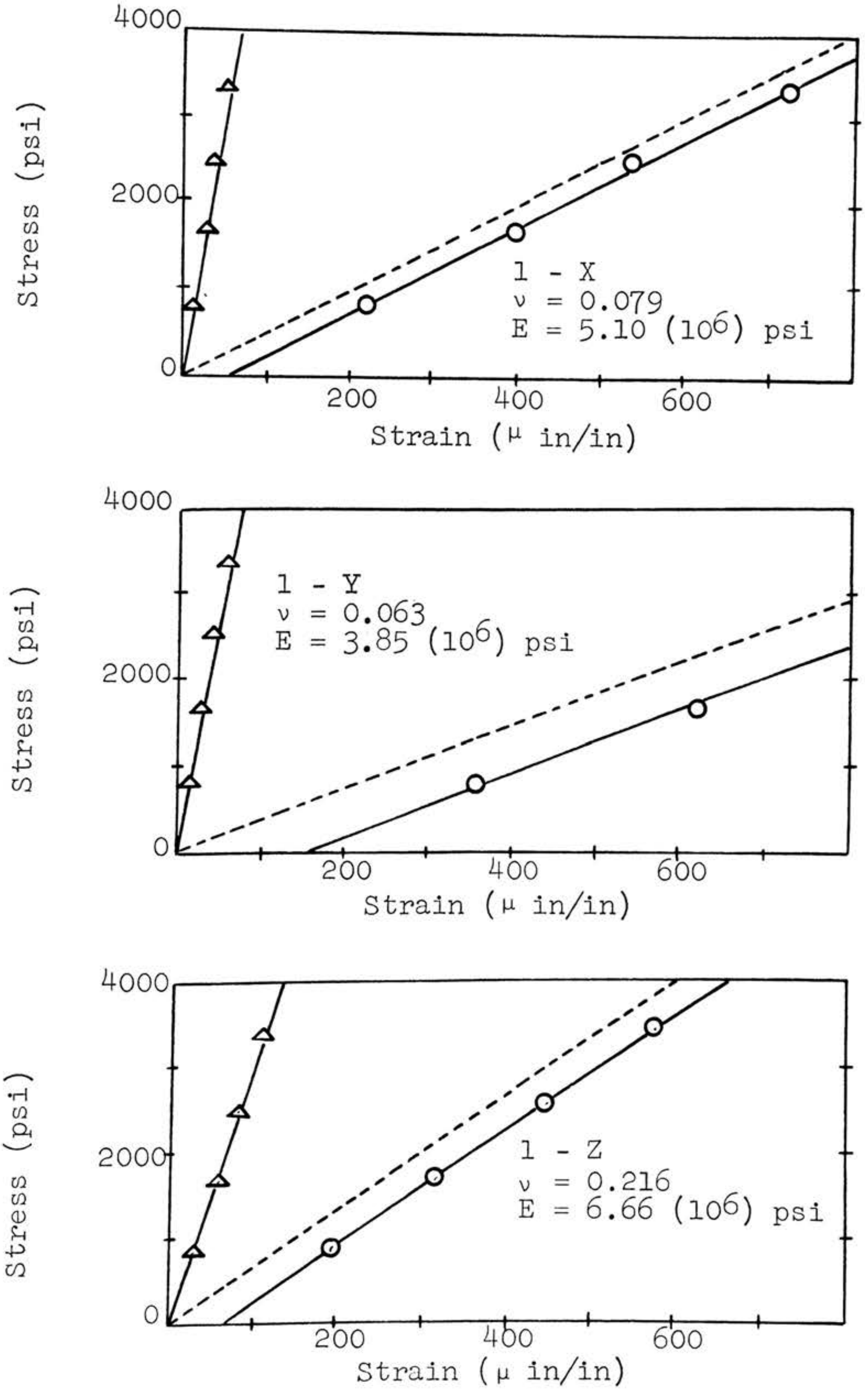


Figure 22. Georgia Granite Specimen No. 1

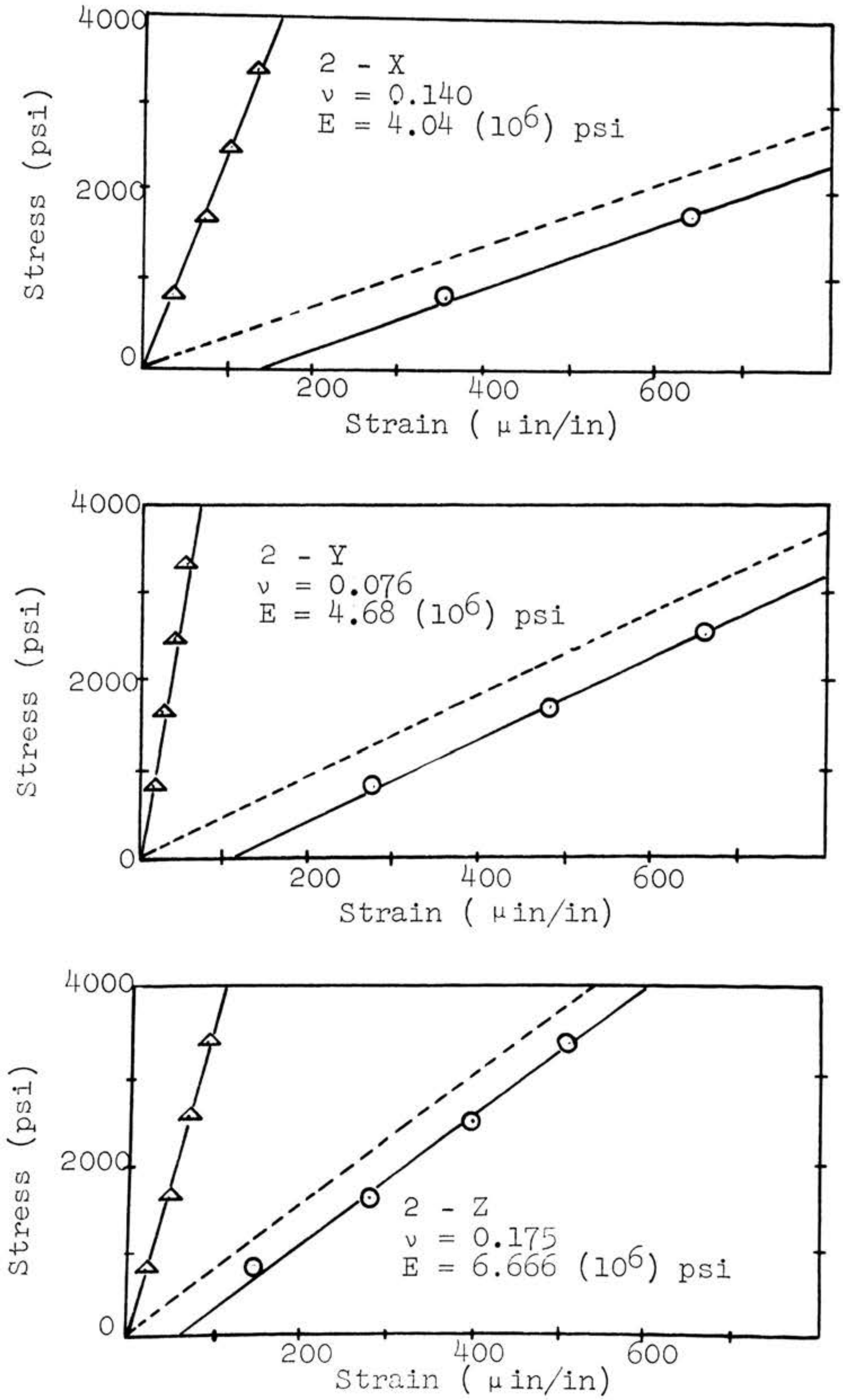


Figure 23. Georgia Granite Specimen No. 2

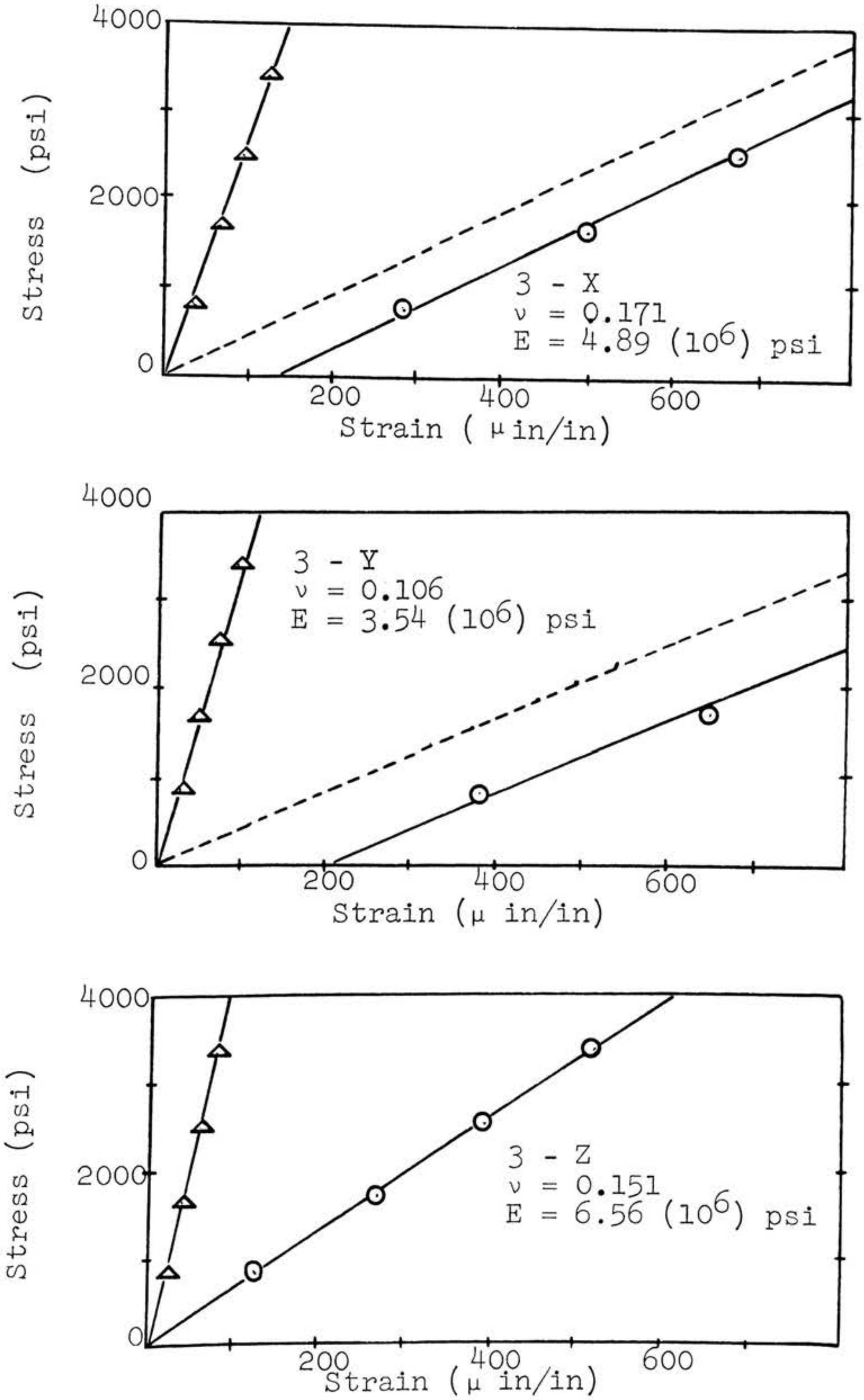


Figure 24. Georgia Granite Specimen No. 3

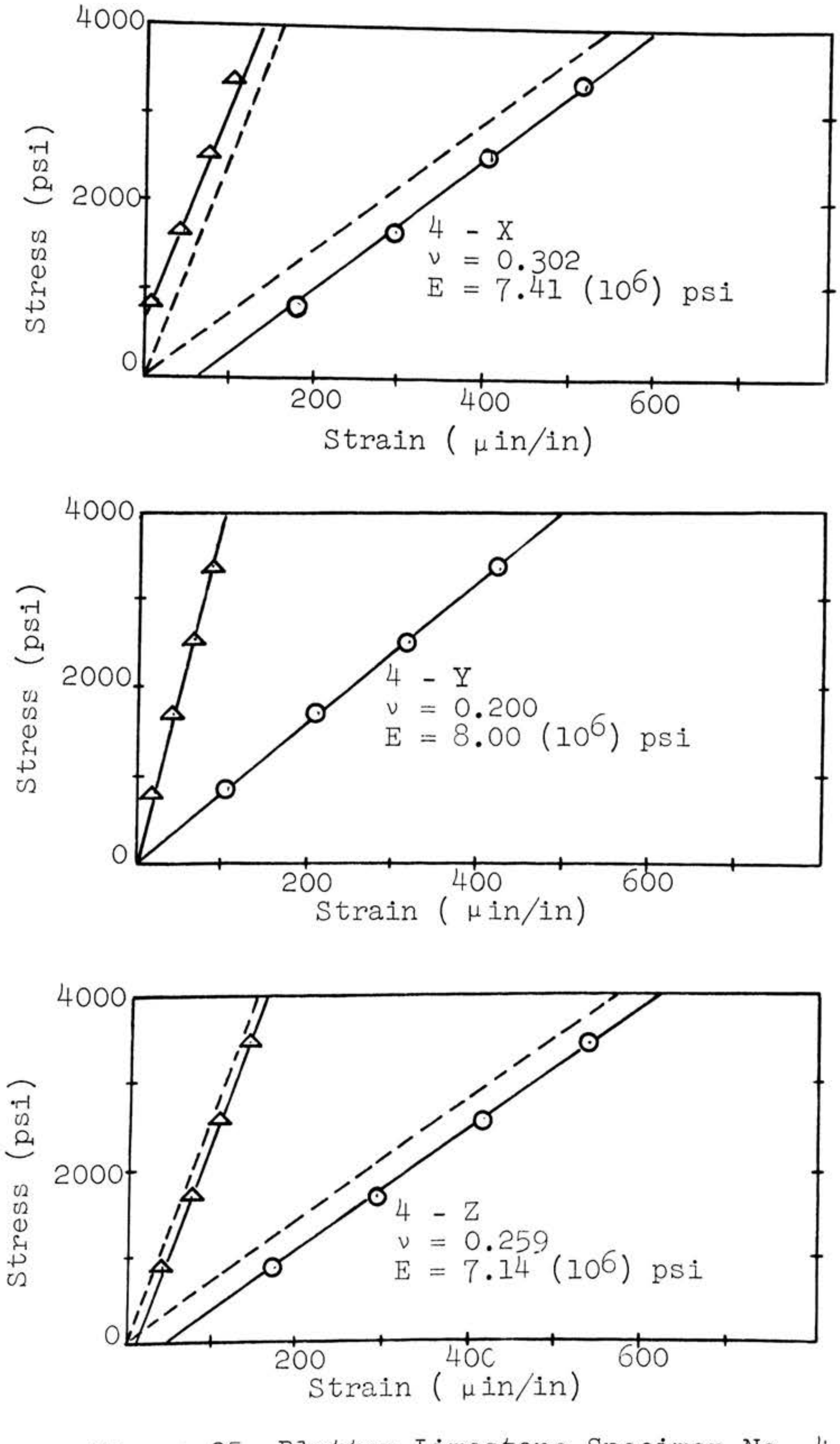


Figure 25 Platten Limestone Specimen No. 4

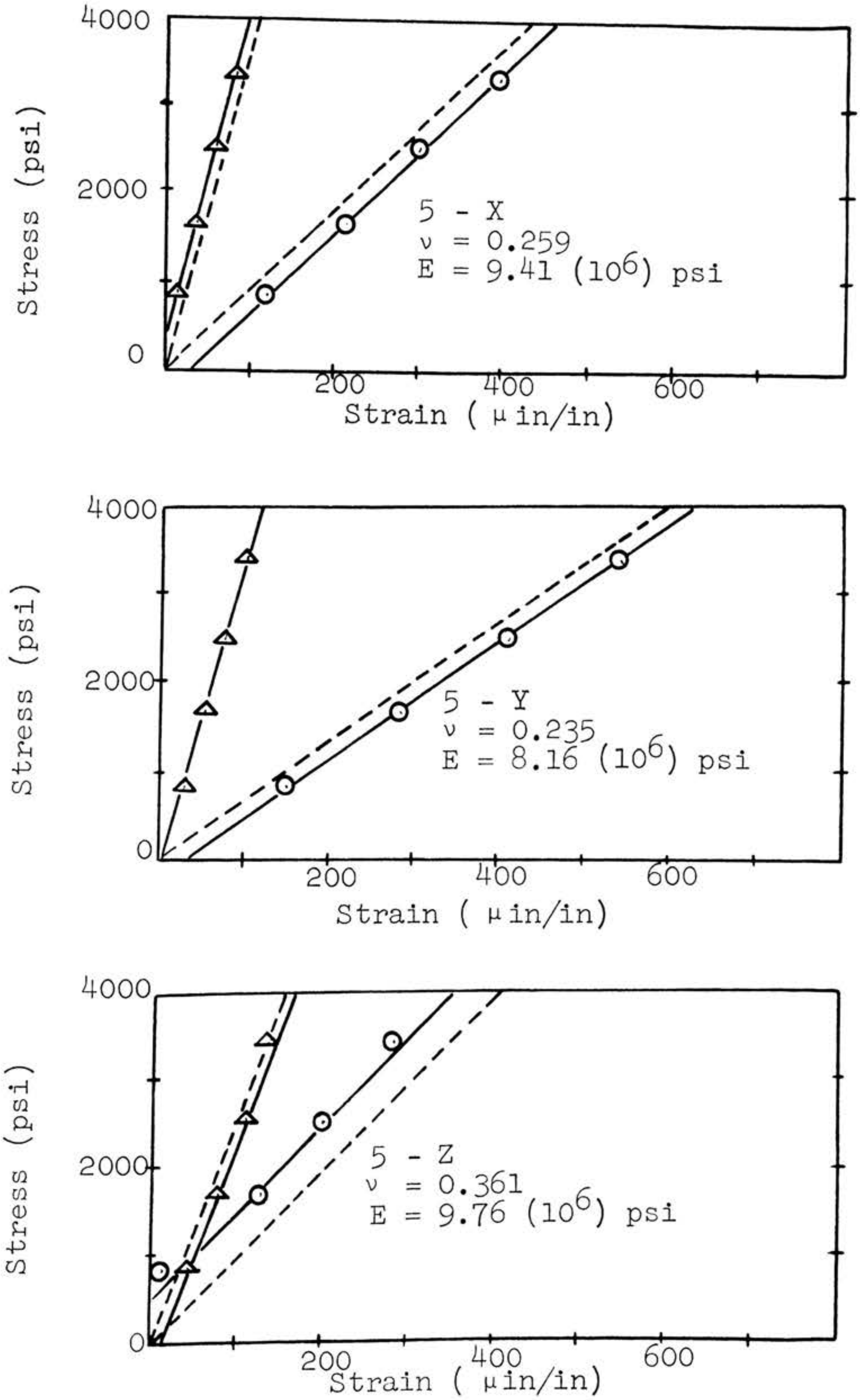


Figure 26. Platten Limestone Specimen No. 5

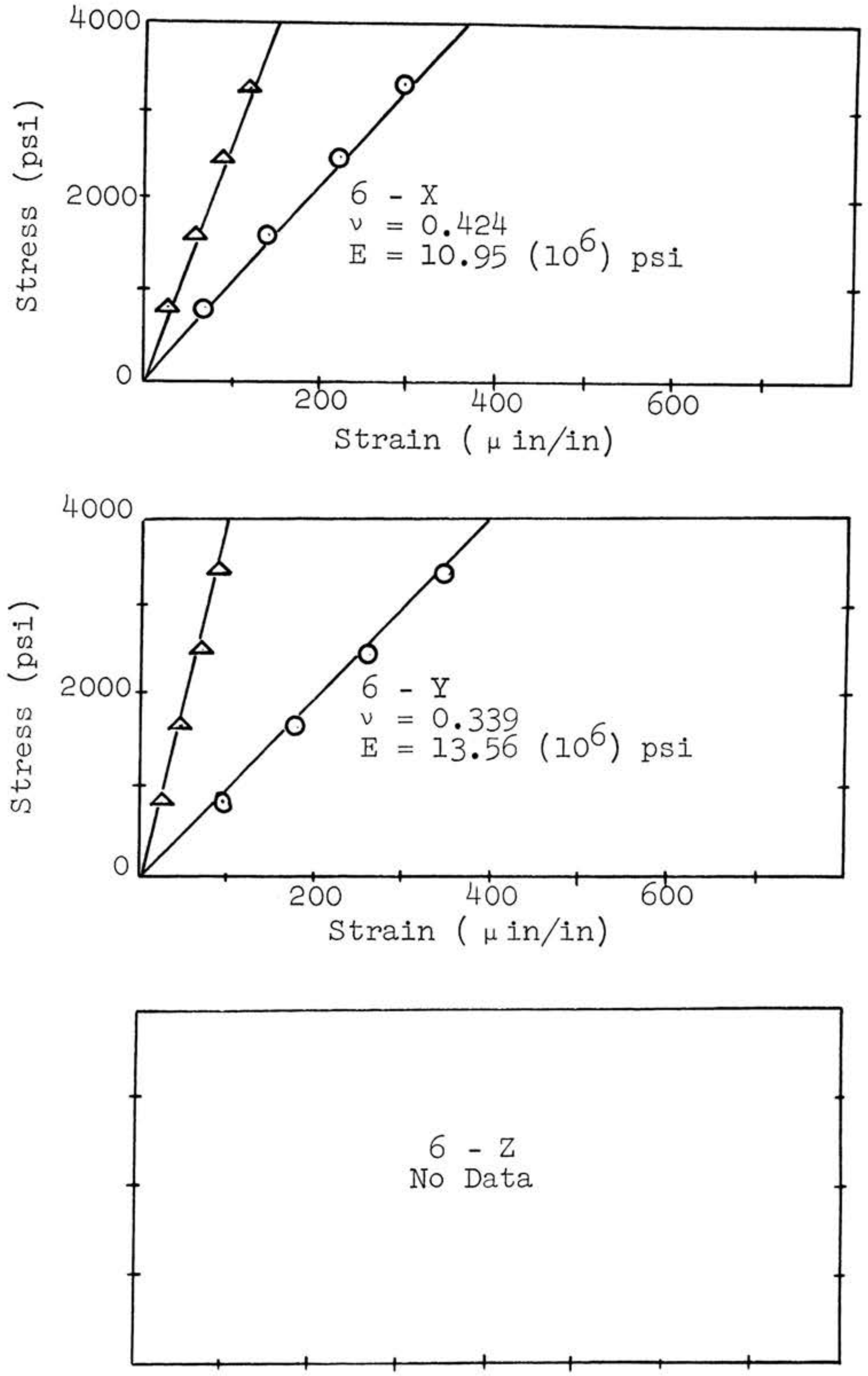


Figure 27. Platten Limestone Specimen No. 6

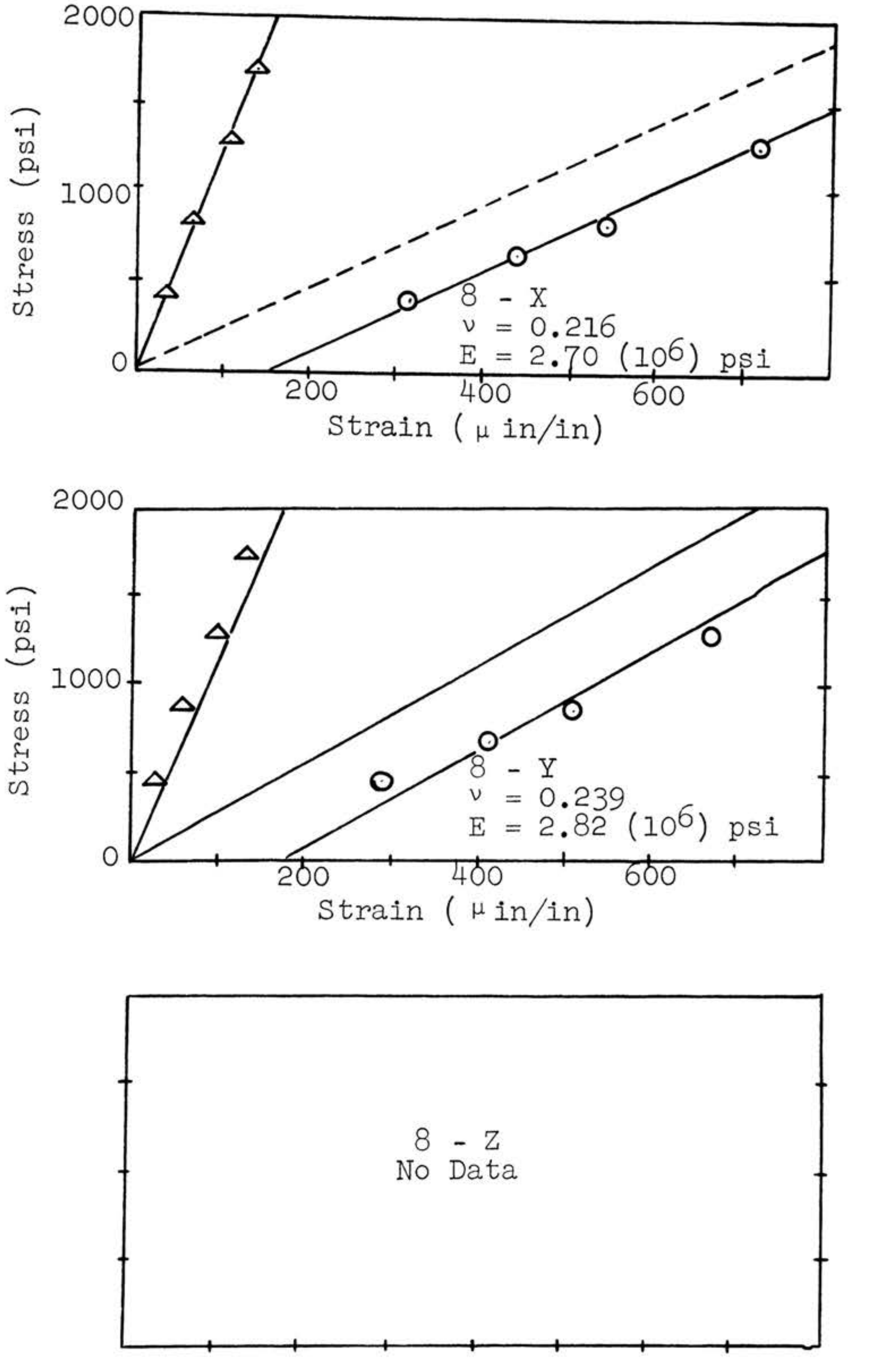


Figure 28. St. Peter Sandstone Specimen No. 8

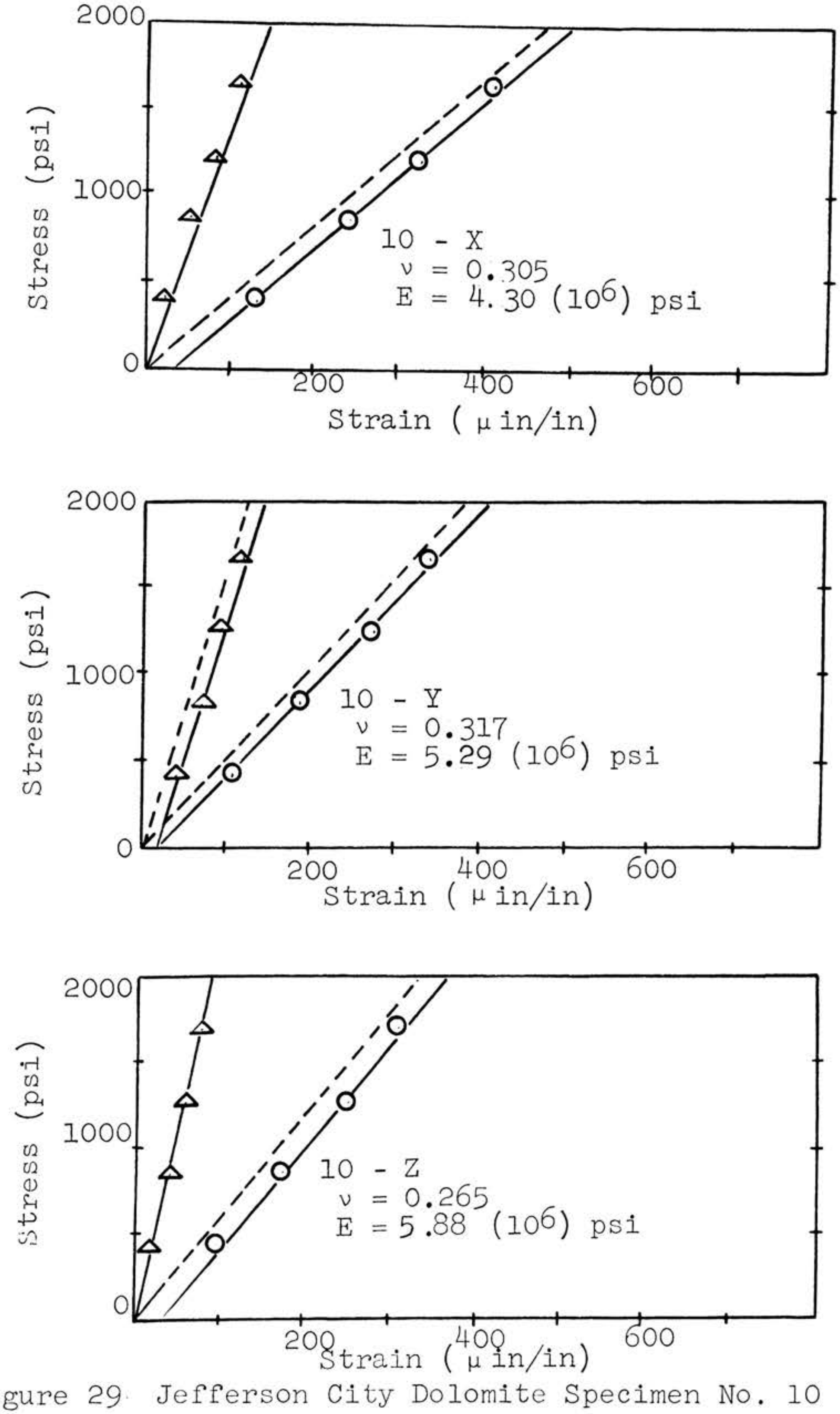


Figure 29 Jefferson City Dolomite Specimen No. 10

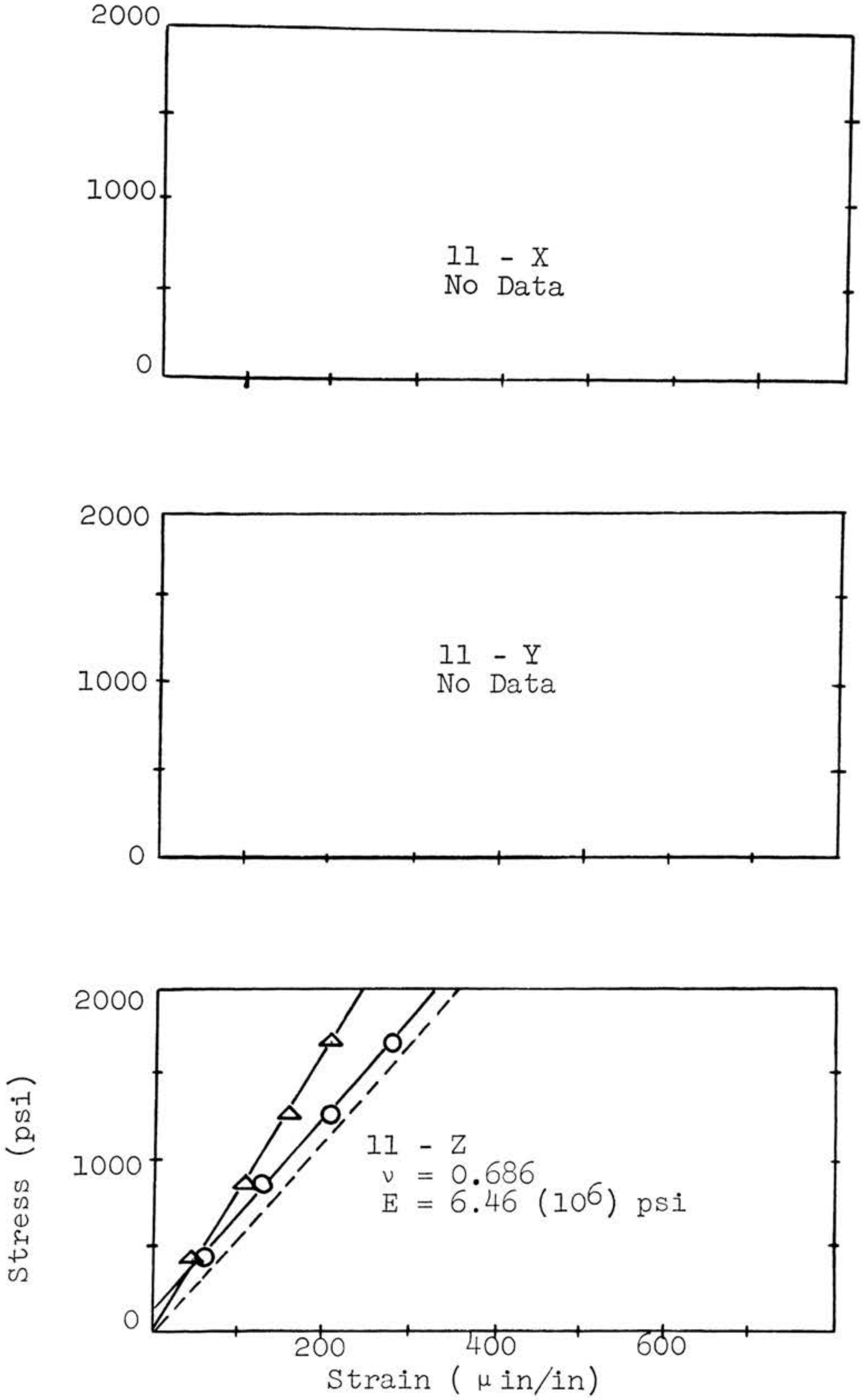


Figure 30. Jefferson City Dolomite Specimen No. 11

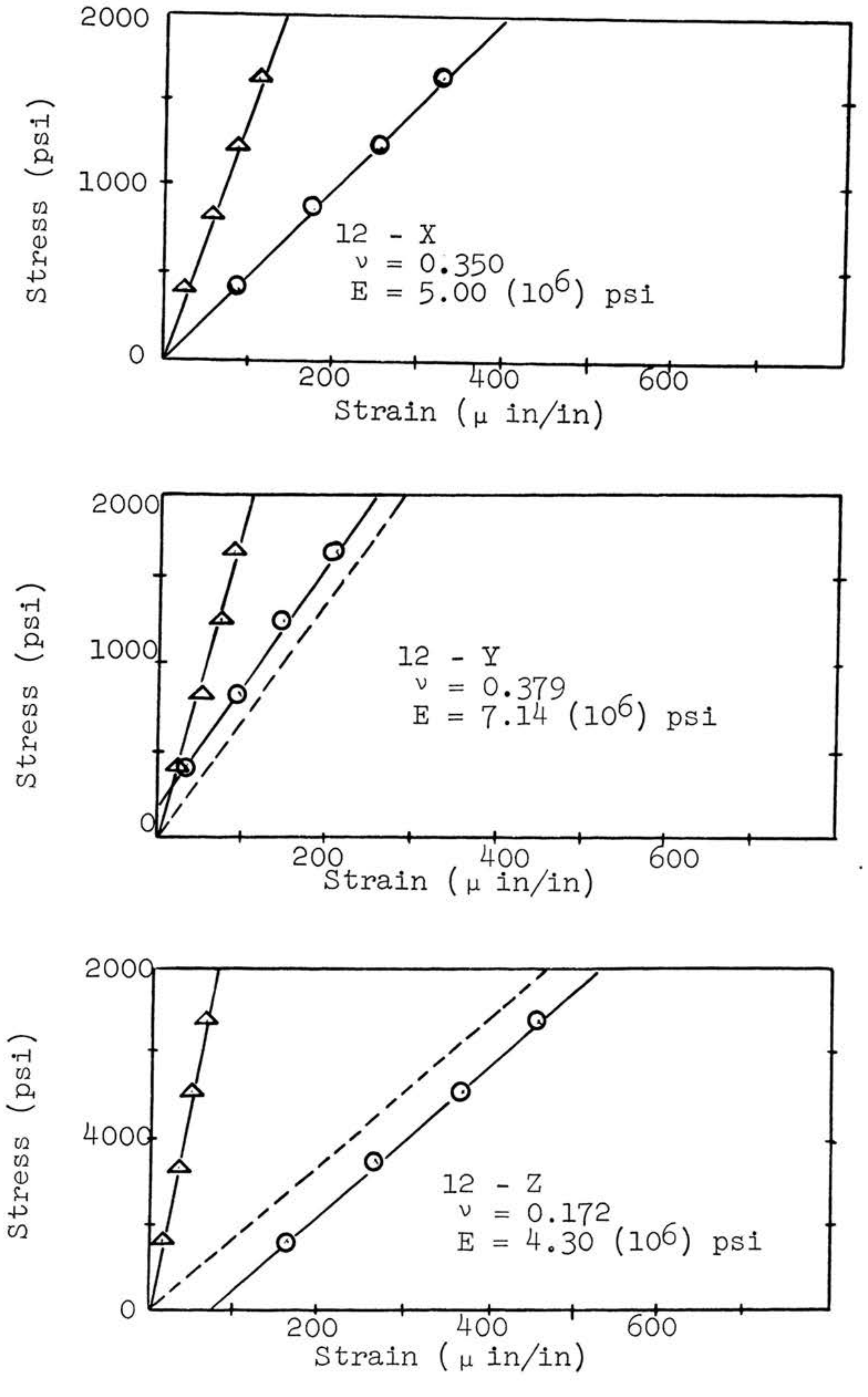


Figure 31 Jefferson City Dolomite Specimen No. 12

CHAPTER V

DISCUSSION

Experimental Problems

In any research of this type, a great deal of time is spent in developing experimental technique and procedure. It is not practical to relate to the reader all of the failures experienced throughout the research; however the principal problem areas are discussed here.

One of the principal problems in conducting the sonic tests was that of maintaining good electrical and mechanical contact between the transducer and the specimen. Aluminum foil, graphite, and silver solder paint were used to obtain an electrical continuity between the transducer and the specimen. During the first stages of the research, aluminum foil was used exclusively, especially in connection with the jig. Results obtained using the aluminum foil were adequate but there was considerable attenuation of the wave in this method.

As the research continued, the technique was modified so that the crystals were glued to the specimen instead of holding them in the jig. In this latter method, good electrical and mechanical contact could not be maintained at the interface with the aluminum foil between the transducer and the specimen. Problems were introduced in gluing the aluminum foil to the specimen. The stability of the aluminum foil when glued on the specimen is questionable. An attempt was made to use powdered graphite to provide electrical contact at the transducer-specimen interface. The powdered graphite is a very good conductor but no method was found to keep the graphite on the specimen while the measurements were being made.

By chance, the silver solder paint was tried as a method of obtaining an electrical contact. The silver solder paint used in these experiments had a lower conductivity than the graphite or aluminum foil, however, the results obtained from this method are much better than either of the other two methods. The paint becomes an integral part of the specimen thus reducing the sharpness of the interfaces which the wave must traverse in passing from the sending transducer into the rock and from the rock into the receiving transducer. The use of the silver solder paint also permits more intimate contact between the transducer and the rock surface than if aluminum foil is used to provide electrical contact.

Another major problem in sonic testing is that the receiving transducer transmits only relatively small voltages to the oscilloscope. The rectangular pulse that drives the source transducer has an amplitude of 100 volts. The voltage output of the receiving transducer has an amplitude ranging from 400 μ volts to five volts. Thus attenuation of the wave becomes a major problem in accurately measuring the desired velocities.

Jones (4) states some of the major causes of attenuation in samples. Imperfections in materials undergoing vibration cause the elastic energy to be dissipated as heat. As this energy is dissipated the vibrations are damped. Voids, cracks, and imperfections are one cause of damping. Another cause is the visco-elastic properties of the material. This will be discussed in greater detail later in this chapter.

The attenuation of a wave passing through limestone or granite was found to be much less than the attenuation of a wave passing through sandstone or dolomite. The explanation of this lies in the fact that both the limestone and granite behave more elastically and have fewer imperfections.

A major problem in the static measurements lies in the bonding of the gages to the rock surface. When coring the specimen it is impossible to eliminate all vibrations from the core drill. Thus the surfaces to which the gages are to be bonded are not uniform. Vugs, such as occur in certain rocks, cause the surface of the core to be pitted. Thus care must be taken in bonding resistance strain gages to rock cores so that the above mentioned factors do not influence the measurements significantly. The cores were sanded with fine sandpaper to produce as smooth a finish as possible,however, nothing was done about the small vugs remaining on the surface. The surface to which the gages were to be applied were cleaned with ethyl acetate just prior to cementing the gages to the rock surface. Placement of the gage was also critical. In one particular limestone specimen a gage was bonded across two crystals. When the core was loaded one crystal appeared to be elastic while the other appeared to be viscous. The result was that erroneous data was obtained. One had to be very careful in placing the gage on the dolomite since there were large vugs in this material, and a gage placed over one of the vugs would give erroneous results. The lengths of the gages were varied from 3/8 in. to 5/8 in. Usually the longer gages were applied to the specimen having the larger crystals; however this was not always so. More meaningful strain determinations could be obtained if a gage the same length as the specimen could be used. Where smaller gages are influenced by the individual crystals, the larger gage would be across all the crystals resulting in a more representative strain reading. In conclusion, one must be very careful to make the specimen as smooth as possible; as clean as possible, and to place the gage in position which gives representative strain readings.

Theoretical Considerations

In order to determine the elastic constants by sonic methods the material being tested should be elastic or nearly so, isotropic, and homogeneous. Any deviation from the above conditions would be a source of error in the determination of the elastic constants.

Sonic velocities were measured along three mutually perpendicular axes on each specimen. No single specimen had the same longitudinal or shear velocity along any two of its three axes. This alone indicates that all of the rocks tested were anisotropic to some degree.

Cracks in the specimen also influence the wave velocities. For instance, if a specimen had a system of cracks that were parallel to the direction of propagation of the longitudinal wave, the wave would propagate somewhat faster through the specimen than if the cracks were perpendicular to the direction of propagation. This same system of cracks would probably also have an effect on the shear wave velocity, however the experimental results did not indicate what the effect would be. The elastic constants computed from these velocities, would therefore be affected by the presence of the cracks.

Nonhomogenity of each of the rock types was verified by visual inspection. Different compositions of the crystals and the matrix of each rock could be clearly seen with a hand lens.

If the horizontal sweep time of the oscilloscope were increased sufficiently it could be seen that the receiving transducer was picking up a wave that was exponentially damped. This would indicate a type of viscous damping in the specimen. Viscous damping implies that the amplitude of the wave is a function of time and distance travelled. Introduction of derivatives with respect to time of stress and strain causes the elastic constants to become complex. The complex modulii, E^*, is given by the equation

$$E^* = E_1(t) + iE_2(t)$$

where E_1 is the elastic modulus and E_2 is the viscous modulus. The magnitude of the imaginary component is in direct proportion to the damping coefficient of the media. Bland (1) discusses visco-elastic wave propagation of various models. An analysis of Bland's equations can become very complex, even for the simplest models.

Discussion of Data

The average per cent deviation of Young's modulus and the shear modulus appears to be approximately 20%. This would seem to be quiet a large deviation until one examines the conditions under which the testing took place. The specimens used in these tests were not specially selected to give optimum test results. Rather they were just as one might take from a mine or dam site for purpose of analysis. With this in mind, the results of the testing appear to be very good.

The results of the tests to determine Poisson's ratio leave something to be desired. The per cent deviation was approximately 50% in the Poisson's ratio determinations.

Georgia Granite

The granite shows a remarkable consistency in the shear velocity, having an average shear velocity of 7500 ft/sec and a deviation of about 300 ft/sec. The longitudinal velocity varied considerably more than the shear velocity. The average velocity was about 12,500 ft/sec with a variation up to 3000 ft/sec.

The granite was the easiest of the four rock types to measure statically. Placement of the gage was never any problem. The crystal sizes were small enough so that the smallest gages could be used effectively The static Poisson's ratio was very small. The average Poisson's ratio was 0.128 while the sonic values tended to be above 0.25. The shear modulus was nearly the same for both the sonic and static techniques.

Platten Limestone

The attenuation of a wave passing through the limestone was less than in any of the other specimens. Young's modulus calculated from the sonic data, averaged about 6×10^6 psi with a maximum deviation of 25%. The trace used to determine the shear velocity showed definite signs of a P wave first arrival. This presented some problems in picking the first shear arrival.

Placement of the gage was an important factor in determining the elastic moduli of the limestone. The individual crystals were large and had a definite effect on the measurements. Young's modulus varied more in the static measurements than in the sonic measurements. The ranges were from 7×10^6 psi to 13×10^6 psi. The static Poisson's ratio again appears to be less than the sonic value.

Jefferson City Dolomite

Of the four rock types, the results obtained from the dolomite were the most consistent. This is very surprising since the dolomite appeared to be the most inelastic of the four types. The dolomite was so vuggy that two of the specimens broke when the end surfaces were being ground for the static tests.

St. Peter Sandstone

The Saint Peter Sandstone was almost impossible to test either by sonic or static methods Neither a shear or longitudinal wave would propagate through the material without a high energy loss. The static measurements were difficult to obtain because the rock shows signs of creep. The reason for the poor measurements was the poor cementation of the sand grains. Two of the specimens were so poorly cemented that it was impossible to core them for the static tests.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

It appears that the four media studied exhibit visco-elastic properties. If the proper visco-elastic model could be found to represent the rocks a much better analysis of the material behavior could be expected.

The visco-elastic damping coefficient, discussed in Chapter V might possibly be determined in a future investigation for various materials using the sonic pulse method.

The effect of cracks on propagation of longitudinal and shear waves would also be a very good topic for additional research.

From the research conducted it would seem that both the sonic Young's modulus and the shear modulus could be used as design parameters when the normal safety factor of four is applied to the design.

The purpose of this research was to develop better techniques of determining sonic elastic moduli such that the results would be reproducible. While the commonly accepted methods of static testing were employed, several significant improvements in the presently existing sonic techniques were made. The use of the silver-solder paint as a conductor and the use of phenyl salicylate for gluing the transducers directly to the rock specimen improved the pulse transmission characteristics considerably over previous methods. The use of longitudinal transducers on a free surface to generate a strong shear wave was a definite improvement in shear wave velocity determinations. The accurate determination of shear wave velocity has always been one of the problem areas in sonic pulse techniques. The problem of correlating static and sonic values of the elastic constants was not resolved as was expected, however the methods described here will yield as good a result as can be expected under the conditions of testing.

BIBLIOGRAPHY

1. Bland, D. R. Theory of Linear Viscoelasticity. Oxford: The University Press, 1960.
2. Clark, G. B. "Deformation Moduli of Rocks", Paper No. 101, Advance Copy of a paper presented at the Fifth Pacific Area National Meeting of American Society for Testing and Materials, Seattle, Washington, October 31 to November 5, 1965.
3. Jamieson, J. C. and Hoskins, H. "The Measurement of Shear-Wave Velocities in Solids Using Axially Polorized Ceramic Transducers," Geophysics, XXVII, No. 1 (February, 1963), pp. 87-90.
4. Jones, R. Non-Destructive Testing of Concrete. Cambridge: Cambridge University Press, 1962.
5. Kolsky, H. Stress Waves in Solids. New York: Dover Publications, Inc. 1963.
6. Obert, L., et. al.. "Standardized Tests for Determining the Physical Properties of Mine Rock", U. S. Bureau of Mines RI 3891, 1946.

VITA

The author was born on November 13, 1941, in Knoxville, Tennessee. He received his primary and secondary education in Knoxville, Tennessee. He has received his college education from the University of Tennessee, in Knoxville, Tennessee; East Tennessee State University, in Johnson City, Tennessee, and the University of Missouri at Rolla. He received a Bachelor of Science Degree in Mining Engineering from the Missouri School of Mines and Metallurgy at Rolla in January 1965 and plans to receive his Master of Science Degree in Mining Engineering In February 1966.

He has been enrolled in Graduate School of the University of Missouri at Rolla since January 1965 and has been a graduate assistante in the Department of Mining Engineering, and has been an instructor in the Department of Mathematics.

APPENDIX I

SONIC DATA

Specimen No. 1 Sonic Velocity Data

<u>Longitudinal Velocity Data</u>

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	5.733	36.0
Y	5.745	48.0
Z	6.017	38.0

<u>Shear Velocity Data</u>

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	5.00	60.0
X	4.00	48.0
X	3.00	34.0
X	2.00	22.0
X	1.00	8.0
Y	4.00	45.0
Y	3.00	35.0
Y	2.00	22.5
Y	1.00	10.5
Z	5.00	58.0
Z	4.00	46.0
Z	3.00	33.0
Z	2.00	21.0
Z	1.00	11.0

Specimen No. 2 Sonic Velocity Data

Longitudinal Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	6.243	52.0
Y	6.169	39.0
Z	5.768	34.5

Shear Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	5.00	58.0
X	4.00	46.0
X	3.00	34.0
X	2.00	22.0
X	1.00	10.0
Y	5.00	54.0
Y	4.00	42.0
Y	3.00	32.0
Y	2.00	22.0
Y	1.00	10.0
Z	5.00	56.0
Z	4.00	47.0
Z	3.00	34.0
Z	2.00	22.0
Z	1.00	10.0

Specimen No. 3 Sonic Velocity Data

Longitudinal Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	6.011	46.0
Y	5.992	36.0
Z	5.766	34.0

Shear Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	5.00	58.0
X	4.00	46.0
X	3.00	34.0
X	2.00	24.0
X	1.00	10.0
Y	5.00	52.0
Y	4.00	42.0
Y	3.00	32.0
Y	2.00	20.0
Y	1.00	10.0
Z	5.00	60.0
Z	4.00	48.0
Z	3.00	34.0
Z	2.00	22.0
Z	1.00	8.0

Specimen No. 4 Sonic Velocity Data

Longitudinal Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	6.730	30.0
Y	5.744	27.0
Z	8.567	40.0

Shear Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	5.00	46.0
X	4.00	34.0
X	3.00	28.0
X	2.00	18.0
X	1.00	9.0
Y	5.00	46.0
Y	4.00	32.0
Y	3.00	26.0
Y	2.00	16.0
Y	1.00	8.0
Z	7.00	66.0
Z	6.00	55.0
Z	5.00	44.0
Z	4.00	36.0
Z	3.00	28.0
Z	2.00	17.0
Z	1.00	8.0

Specimen No. 5 | Sonic Velocity Data

Longitudinal Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	8.476	42.0
Y	5.615	28.0
Z	6.507	32.0

Shear Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	7.00	70.0
X	6.00	60.0
X	5.00	50.0
X	4.00	40.0
X	3.00	30.0
X	2.00	20.0
X	1.00	10.0
Y	4.00	40.0
Y	3.00	30.0
Y	2.00	19.0
Y	1.00	9.0
Z	5.00	47.0
Z	4.00	39.0
Z	3.00	29.0
Z	2.00	18.0
Z	1.00	8.0

Specimen No. 6 Sonic Velocity Data

<u>Longitudinal Velocity Data</u>

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	5.499	30.0
Y	7.636	46.0
Z	8.015	38.0

<u>Shear Velocity Data</u>

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	4.00	40.0
X	3.00	30.0
X	2.00	20.0
X	1.00	10.0
Y	6.00	63.0
Y	5.00	48.0
Y	4.00	40.0
Y	3.00	32.0
Y	2.00	21.0
Y	1.00	10.0
Z	7.00	66.0
Z	6.00	59.0
Z	5.00	49.0
Z	4.00	36.0
Z	3.00	25.0
Z	2.00	16.0
Z	1.00	3.5

Specimen No. 7 Sonic Velocity Data

Longitudinal Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	5.908	100.0
Y	7.235	110.0
Z	7.205	124.0

Shear Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	4.00	100.0
X	3.00	75.0
X	2.00	No Data
X	1.00	No Data
Y	6.00	140.0
Y	5.00	100.0
Y	4.00	76.0
Y	3.00	60.0
Y	2.00	24.0
Y	1.00	18.0
Z	6.00	160.0
Z	5.00	130.0
Z	4.00	100.0
Z	3.00	60.0
Z	2.00	40.0
Z	1.00	20.0

Specimen No. 8 | Sonic Velocity Data

Longitudinal Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	6.620	62.0
Y	6.493	62.0
Z	5.090	62.0

Shear Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	5.00	72.0
X	4.00	62.0
X	3.00	44.0
X	2.00	30.0
X	1.00	14.0
Y	5.00	70.0
Y	4.00	54.0
Y	3.00	42.0
Y	2.00	30.0
Y	1.00	15.0
Z	4.00	56.0
Z	3.00	42.0
Z	2.00	32.0
Z	1.00	14.0

Specimen No. 9 Sonic Velocity Data

Longitudinal Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	6.420	85.0
Y	6.387	75.0
Z	6.405	92.0

Shear Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	5.00	100.0
X	4.00	80.0
X	3.00	60.0
X	2.00	40.0
X	1.00	No Data
Y	4.00	75.0
Y	3.00	55.0
Y	2.00	45.0
Y	1.00	22.0
Z	5.00	100.0
Z	4.00	80.0
Z	3.00	60.0
Z	2.00	40.0
Z	1.00	No Data

Specimen No. 10 — Sonic Velocity Data

Longitudinal Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	5.454	30.0
Y	6.951	40.0
Z	5.518	30.0

Shear Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	4.00	45.0
X	3.00	30.0
X	2.00	20.0
X	1.00	10.0
Y	6.00	70.0
Y	5.00	60.0
Y	4.00	50.0
Y	3.00	40.0
Y	2.00	20.0
Y	1.00	12.0
Z	4.00	33.0
Z	3.00	21.0
Z	2.00	16.0
Z	1.00	11.0

Specimen No. 11

Sonic Velocity Data

Longitudinal Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	5.624	32.0
Y	6.218	40.0
Z	4.265	20.0

Shear Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	4.00	40.0
X	3.00	30.0
X	2.00	20.0
X	1.00	10.0
Y	5.00	60.0
Y	4.00	42.0
Y	3.00	36.0
Y	2.00	20.0
Y	1.00	10.0
Z	3.00	30.0
Z	2.00	20.0
Z	1.00	10.0

Specimen No. 12 Sonic Velocity Data

Longitudinal Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	4.785	25.0
Y	6.192	38.0
Z	5.663	34.0

Shear Velocity Data

Axis of Orientation	Length (in.)	Travel Time (μ sec.)
X	4.00	46.0
X	3.00	30.0
X	2.00	20.0
X	1.00	10.0
Y	5.00	60.0
Y	4.00	48.0
Y	3.00	32.0
Y	2.00	18.0
Y	1.00	10.0
Z	4.00	50.0
Z	3.00	40.0
Z	2.00	27.0
Z	1.00	10.0

APPENDIX II

STATIC DATA

Specimen No. 1 Static Data

Axis of Orientation	Load (pounds)	Lat. Strain (μ in/in)	Long. Strain (μ in/in)
X	2000	16	223
	4000	25	398
	6000	36	578
	8000	50	720
	6000	34	580
	4000	23	440
	2000	10	266
	0	0	5
Y	2000	12	367
	4000	28	625
	6000	44	828
	8000	62	1018
	6000	43	854
	4000	25	672
	2000	10	428
	0	0	4
Z	2000	30	170
	4000	54	314
	6000	78	450
	8000	104	574
	6000	78	464
	4000	53	342
	2000	30	188
	0	3	0

Specimen No. 2 Static Data

Axis of Orientation	Load (pounds)	Lat. Strain (μ in/in)	Long. Strain (μ in/in)
X	2000	36	352
	4000	70	640
	6000	98	810
	8000	128	1070
	6000	100	910
	4000	68	704
	2000	35	426
	0	-8	4
Y	2000	10	268
	4000	20	475
	6000	34	652
	8000	45	825
	6000	32	685
	4000	18	524
	2000	6	323
	0	0	2
Z	2000	22	146
	4000	42	280
	6000	62	400
	8000	85	510
	6000	63	400
	4000	40	290
	2000	18	150
	0	2	0

Specimen No. 3 Static Data

Axis of Orientation	Load (pounds)	Lat. Strain (μ in/in)	Long. Strain (μ in/in)
X	2000	28	280
	4000	58	495
	6000	86	670
	8000	116	830
	6000	90	692
	4000	65	534
	2000	35	316
	0	0	0
Y	2000	24	248
	4000	42	423
	6000	65	775
	8000	88	1024
	6000	66	838
	4000	48	644
	2000	26	380
	0	0	5
Z	2000	17	123
	4000	35	267
	6000	56	396
	8000	78	520
	6000	56	414
	4000	36	294
	2000	16	154
	0	5	5

Specimen No. 4 Static Data

Axis of Orientation	Load (pounds)	Lat. Strain (μ in/in)	Long. Strain (μ in/in)
X	2000	19	176
	4000	47	290
	6000	78	407
	8000	107	520
	6000	78	410
	4000	50	300
	2000	24	180
	0	0	0
Y	2000	21	108
	4000	42	214
	6000	61	318
	8000	83	424
	6000	62	330
	4000	42	230
	2000	20	122
	0	0	7
Z	2000	40	158
	4000	70	288
	6000	100	410
	8000	133	536
	6000	103	418
	4000	70	300
	2000	36	170
	0	0	5

Specimen No. 5 Static Data

Axis of Orientation	Load (pounds)	Lat. Strain (μ in/in)	Long. Strain (μ in/in)
X	2000	17	122
	4000	36	210
	6000	57	300
	8000	79	391
	6000	57	301
	4000	37	210
	2000	17	110
	0	3	3
Y	2000	30	150
	4000	52	287
	6000	75	412
	8000	98	544
	6000	76	424
	4000	54	306
	2000	30	172
	0	0	0
Z	2000	40	45
	4000	73	123
	6000	103	200
	8000	135	282

Specimen No. 6 Static Data

Axis of Orientation	Load (pounds)	Lat. Strain (μ in/in)	Long. Strain (μ in/in)
X	2000	25	66
	4000	57	138
	6000	88	213
	8000	118	286
	6000	88	210
	4000	60	140
	2000	28	64
	0	0	0
Y	2000	24	91
	4000	46	174
	6000	69	257
	8000	90	348
	6000	69	253
	4000	47	170
	2000	23	89
	0	2	5
Z	No Data		

Specimen No. 8 Static Data

Axis of Orientation	Load (pounds)	Lat. Strain (μ in/in)	Long. Strain (μ in/in)
X	1000	32	318
	2000	65	540
	3000	102	712
	4000	133	858
	3000	112	740
	2000	88	597
	1000	54	405
Y	1000	28	290
	2000	60	510
	3000	98	670
	4000	130	810
	3000	118	707
	2000	99	565
	1000	62	375
	0	0	7
Z	No Data		

Specimen No. 10 Static Data

Axis of Orientation	Load (pounds)	Lat. Strain (μ in/in)	Long. Strain (μ in/in)
X	1000	24	130
	2000	52	240
	3000	80	322
	4000	106	408
	3000	82	336
	2000	57	257
	1000	28	158
	0	0	0
Y	1000	41	108
	2000	70	186
	3000	94	268
	4000	116	337
	3000	96	272
	2000	74	204
	1000	44	120
	0	0	0
Z	1000	18	94
	2000	37	170
	3000	56	247
	4000	78	310
	3000	58	250
	2000	36	186
	1000	17	112
	0	0	6

Specimen No. 11 Static Data

Axis of Orientation	Load (pounds)	Lat. Strain (μ in/in)	Long. Strain (μ in/in)
X	No Data		
Y	No Data		
Z	1000	38	30
	2000	62	55
	3000	80	90
	4000	110	128
	5000	126	160
	6000	154	200
	7000	177	237
	8000	205	275
	0	13	6

Specimen No. 12 Static Data

Axis of Orientation	Load (pounds)	Lat. Strain (μ in/in)	Long. Strain (μ in/in)
X	1000	26	90
	2000	55	175
	3000	80	253
	4000	108	324
	3000	84	257
	2000	56	186
	1000	28	100
	0	0	0
Y	1000	30	34
	2000	48	90
	3000	70	145
	4000	84	205
	3000	68	150
	2000	50	87
	1000	32	26
	0	5	5
Z	1000	15	163
	2000	33	267
	3000	46	370
	4000	64	456
	3000	46	379
	2000	33	298
	1000	17	185
	0	0	7