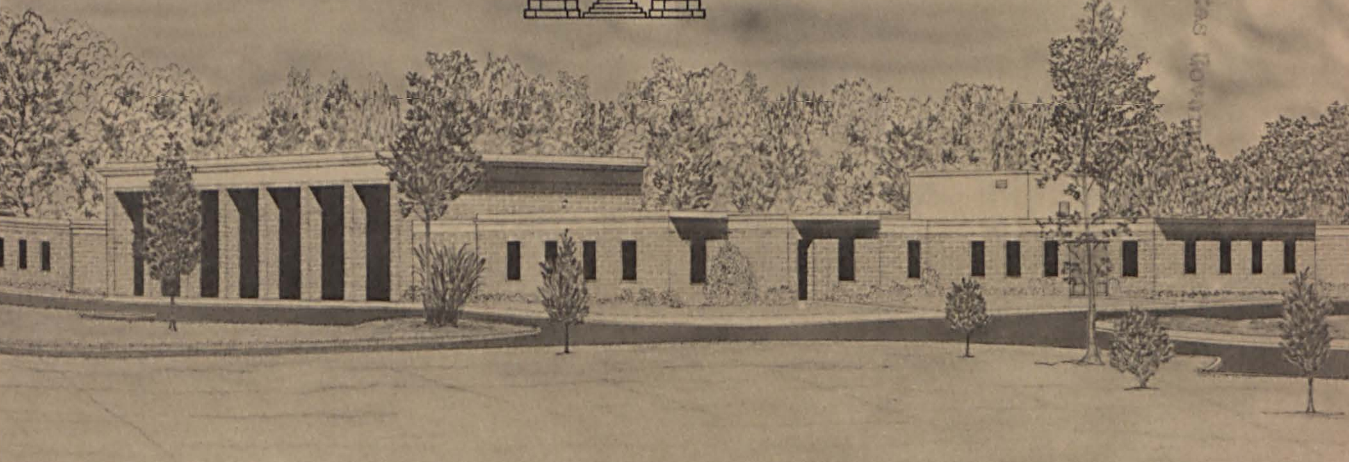
MISCELLANEOUS PAPER C-71-2

THE INFLUENCE OF VARIATION IN GRAIN SIZE AND MINIMAL VARIATION IN ROCK TYPE ON THE QUALITY OF ROCK PROPERTY CORRELATIONS FOR INTACT IGNEOUS ROCKS

by

R. W. Crisp



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FOREWORD

This report is based on a thesis prepared by Mr. Robert W. Crisp of the Concrete Division of the U. S. Army Engineer Waterways Experiment Station (WES) in partial fulfillment of the requirements for the degree of Master of Science in the Department of Civil Engineering, Mississippi State University.

The investigation was conducted at the Concrete Division, WES, from June 1970 to September 1970. Mr. C. R. Hallford performed the petrographic analysis.

Directors of the WES during the conduct of the investigation and the preparation and publication of this report were COL Levi A. Brown, CE, and COL Ernest D. Peixotto, CE. Technical Director was Mr. F. R. Brown.

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CHAPTER 1

INTRODUCTION

Background

Efforts exerted over the past several years to develop techniques and standards to allow for the competent design and construction of engineering structures in rock have led to the establishment of several particular mechanical rock properties in positions of prominence. According to Obert (9)*, these "most important physical properties for design purposes are density, Young's modulus, compressive strength, and flexural strength."

The determination of such physical properties, accomplished through laboratory testing of samples of rock core and field testing of portions of the in-situ rock mass, is, as a rule, quite time consuming and expensive. It is for this reason that correlations of physical properties of rock, and predictions of one property from an already determined value of another property, should be tremendous assets, provided the quality of the correlations is such that the element of doubt regarding test results and predicted properties is not of a magnitude necessitating an increase in the factor of safety.

One particular situation in which such correlations would prove of value might be the site evaluation and selection program.

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*Numbers in parenthesis refer to references in the Bibliography.

Assuming several sites were being considered for a particular structural endeavor, preliminary elimination might well be facilitated if one or two of the less time consuming and less expensive physical tests would yield data from which one could reasonably predict other, more difficult to determine, physical properties to be used in the evaluation and elimination process. It is also possible that correlations such as these, if of sufficient quality, would allow for reduction in the variety of tests required to determine the physical properties now deemed necessary for competent design and construction in rock media.

Another significant application of physical property correlations might be the elimination of some destructive physical testing, to be replaced by nondestructive testing. As indicated by Obert (8), nondestructive tests can be repeated a number of times on the same specimens, facilitating determination of and compensation for procedural and instrument errors. This would allow one to separate the variations due to instrument error from the variations due to actual differences in mechanical properties of the specimens tested.

Previous Studies

In the past, laboratory investigations and correlations of physical properties of rock have generally been limited to intact specimens, i.e., rock cores which are macroscopically homogeneous and free of discontinuities such as seams, joints, fractures, and inclusions. However, even when these investigations have been restricted to intact rock, thus eliminating the highly variable fracture parameter, data plots have frequently been highly scattered in nature resulting in correlations of questionable value.

Usually, investigations of this nature have encompassed many rock types (3) (4) (6) (7), the determined physical properties for all rock types being lumped together and analyzed in mass. This procedure is oriented toward determining general relationships characteristic of the entire group of specimens examined. But the implication here, namely that large variations in mineral composition, geologic history, and grain size (which usually enter into the classification of rock materials) have little or no effect on the relationships between physical properties, is dubious (10).

Thus, a definite need exists to investigate the relationships between various rock properties, focusing attention on individual rock types in an attempt to reduce the number of variables and eliminate some of the scatter typical of previous investigations. Hopefully, the resulting correlations will be of a quality which will allow for the elimination of repetitive testing and data reduction, facilitating more economic design of engineering structures.

Objectives of This Investigation

This study will be primarily directed toward determining the influence of variation in rock type on the quality of correlations obtained through linear correlation analysis of various physical rock properties. An attempt will also be made to determine the effect of variation in grain size within a particular rock type on the nature of the correlations between physical properties determined for specimens of this rock type.

Specimens of tonalite and granite will be prepared and tested, the following physical properties being determined:

(a) density

(b) compressional pulse velocity

(c) shear pulse velocity

(d) Young's modulus of elasticity (static)

(e) ultimate uniaxial compressive strength.

Pulse velocities will be determined according to the ASTM proposed Standard Method of Test for Laboratory Determination of Ultrasonic Pulse Velocities and Elastic Constants of Rock. Ultrasonic elastic constants will be computed from properties 1, 2, and 3. Static Young's modulus will be computed from stress-strain curves determined during uniaxial compressive tests. Representative specimens will be subjected to petrographic examination (X-ray diffraction analysis, modal analysis, etc.). In as far as is possible, the specimens of tonalite and granite will represent samples of various grain sizes, and mineral composition will be varied within the limits of the classification system (11). All specimens will be intact, i.e., free of macroscopic discontinuities such as fractures, joints, seams, and vesicles.

The data accumulated will be grouped and analyzed according to rock type, and then, for comparative purposes, analyzed in mass. Correlations will be made between various pairs of the physical properties determined. In particular, ultimate uniaxial compressive strength and static Young's modulus will each be correlated with ultrasonic pulse velocities and the various ultrasonic elastic constants. Comparisons will be made of the quality of correlations obtained from the data grouped according to rock type and from the data treated in their entirety, and an effort made to determine the influence of data analysis by rock type on quality of the correlations obtained.

Correlations will be made using physical properties determined for three groups of specimens within one particular rock type (tonalite). These three groups will be essentially of the same mineral composition and geologic history, the variable being grain size. The intention will be to evaluate the contribution of variation in grain size to the nature of the physical property correlations obtained within the particular rock type.

CHAPTER 2

EXPERIMENTAL TECHNIQUE

General

Seventy-nine samples of rock core representing two rock types (granite and tonalite) were prepared and tested in the course of this investigation. These specimens were removed from 10 drill sites in six geographic localities. Generally, eight specimens of one particular rock type, either granite or tonalite, were selected from the core from each of the drill sites. All specimens tested were intact (contained no macroscopic joints or fractures) and essentially homogeneous NX-size (nominal 2-1/8-inch diameter) cylindrical cores.

Tests were conducted during this investigation to determine the following:

(a) rock type and mineral composition

(b) bulk density

(c) ultrasonic pulse velocities (compressional and shear)

(d) ultimate uniaxial compressive strength

(e) static stress-strain relations.

Ultrasonic elastic constants were computed from measured ultrasonic pulse velocities and specific gravities. Static Young's moduli were determined from the axial stress-strain relations observed and recorded during the uniaxial compressive tests.

Petrographic Examination

One representative specimen from each of the 10 groups (10 drill sites) was selected for limited petrographic examination. These specimens were sawed axially, one sawed surface of each specimen being polished and photographed at normal size.

Composite samples were taken from the remaining portions of the selected specimens, and ground into a fine powder so as to pass a No. 325 sieve (44μ). X-ray diffraction patterns were made of each sample. These patterns were then examined to make mineralogical identifications and comparisons. Small portions of each of these powdered samples were tested in dilute hydrochloric (HCl) acid and with a magnetized needle to detect the presence of carbonate minerals and magnetic minerals, respectively. All X-ray patterns were made with an XRD-5 diffractometer using nickel-filtered cooper radiation.

Thin sections were prepared from each specimen and examined with a Spencer polarizing microscope. A point-count modal analysis was made on each thin section to determine the mineral composition by percent and grain size (13) of each of the rocks represented. The number of counts per section was held constant (500), but spacing of the counter was varied with grain size in an attempt to obtain a representative statistical average (2).

A summary of the results of the petrographic examination of representative samples from each of the 10 groups of core is given below. Detailed results are given in Appendix 1.

(a) Tonalite (Vermilion granite formation, Minnesota). Brownish-gray, medium- to coarse-grained. Sections were massive and unweathered. Biotite was broken and altered to chlorite. Microcline was unaltered and unbroken. Very few microfractures were detected.

(b) Granite (Lucerne Pluton, Maine). Black and white. Coarse-grained porphyritic texture. Biotite was unaltered. Plagioclase was slightly altered to sericite. Specimens were unweathered and contained very few microfractures.

(c) Granite (Granite Mountains Uplift, Wyoming). Unweathered, brownish-gray, coarse-grained. Microcline was unaltered. Plagioclase was altered to sericite. Biotite was slightly altered to chlorite. Microfractures were somewhat common.

(d) Tonalite (Sierra Nevada Batholith, California). Fine-grained, dark colored rock. Sections were fresh and contained no macrofractures. Contains principally plagioclase feldspar and biotite mica with smaller amounts of quartz and hornblende.

(e) Tonalite (Sierra Nevada Batholith, California). Medium- to coarse-grained igneous rock. Sections were fresh and intact. Similar in composition to fine-grained rock discussed above.

(f) Tonalite (Sierra Nevada Batholith, California). Medium-grained igneous rock; much finer grained than medium- to coarse-grained tonalite (e). Similar in mineral composition to the two tonalites discussed immediately before (d and e) except slightly more biotite and slightly less hornblende. Also contains very small amounts of magnetite.

(g) Granite (Northwest of Lone Grove Pluton and Enchanted Rock Batholith, Texas). Medium-grained, red granite. Sections were intact and unweathered. Slight alteration of microcline and plagioclase. More muscovite mica present than biotite mica.

(h) Granite (Sherman Granite Facies of Southern Laramie Range, Wyoming). Coarse-grained, light-gray granite. No preexisting fracture surfaces could be detected. Largely composed of quartz, potassium feldspar, plagioclase feldspar, and biotite, with lesser amounts of hornblende.

(i) Granite (Laramie Range, Wyoming). Medium- to coarse-grained, pink granite. Porphyritic texture. Sections were macroscopically free of fractures and were unweathered. Predominately composed of quartz, plagioclase feldspar, potassium feldspar with lesser amounts of hornblende biotite and chlorite.

(j) Tonalite (Cedar City Tonalite, Utah). Medium-grained, gray tonalite. Consisted primarily of plagioclase feldspar, quartz, and hornblende with lesser amounts of potassium feldspar, biotite, and magnetite. Biotite was slightly altered to chlorite.

Specimen Preparation

Test specimens were prepared as suggested in the ASTM proposed "Standard Method of Test for Unconfined Compressive Strength of Rock Core Specimens" and Corps of Engineers Standard Method of Test for Triaxial Strength of Undrained Rock Core Specimens (12), CRD-C 147. When prepared according to the above specifications, specimen tolerances were well within the limits required by the ASTM proposed "Standard Method of Test for Laboratory Determination of Ultrasonic Pulse Velocities and Elastic Constants of Rock.

All samples were cut to lengths of approximately 4.32 inches with a Covington (Figure 1) slab saw (16-inch diameter diamond blade). This specimen length was selected in order to meet the specified length to diameter ratio requirements ($2.0 \leq L/D \leq 2.5$). Since specimen diameter ranged from 2.06 to 2.16 inches, probably due to variation in rock type, bit wear, and drilling technique, the actual length to diameter ratios also varied slightly, but were in all cases greater than 2.0 and less than 2.5.

During the cutting process, specimens were secured in a vise (Figure 2) which aided in alignment and provided for cutting surfaces nearly perpendicular to the axis of the core. A solution of water and soluble oil was used as blade lubricant and coolant. All specimens were thoroughly washed immediately subsequent to cutting to remove any solution which might adhere to the specimen surface. Feed rate was adjusted such that one cut across a diameter required approximately 15 minutes.

After cutting, the ends of all specimens were ground smooth, parallel to each other, and perpendicular to the axis of the core with a Norton hydraulic surface grinder (Figure 3). This surface finishing was pursued in such a manner that specimen ends were flat to within 0.001 inches and did not depart from perpendicularity to the axis of the core by more than the allowable 0.01 inch in 2 inches (0.25 degrees). Subsequent to grinding, the specimens were again thoroughly washed to remove any of the oil-water grinding wheel coolant solution from the core surfaces.

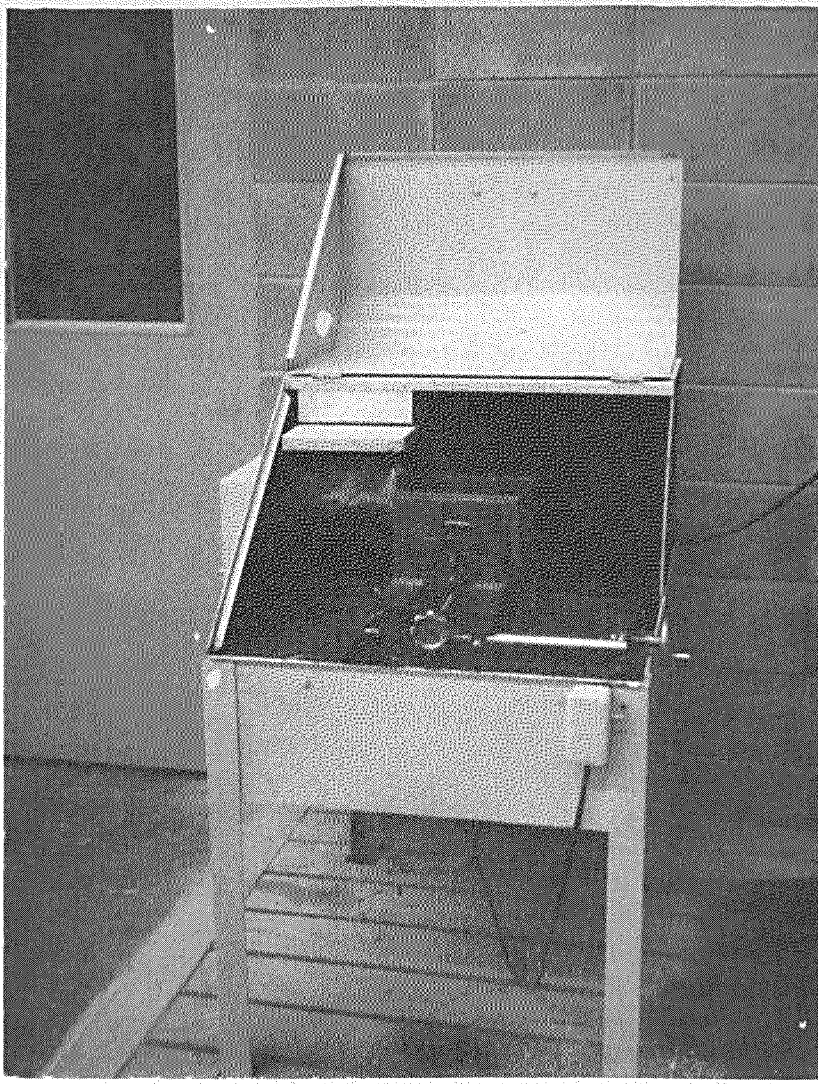


Figure 1. Diamond Blade Slab Saw.

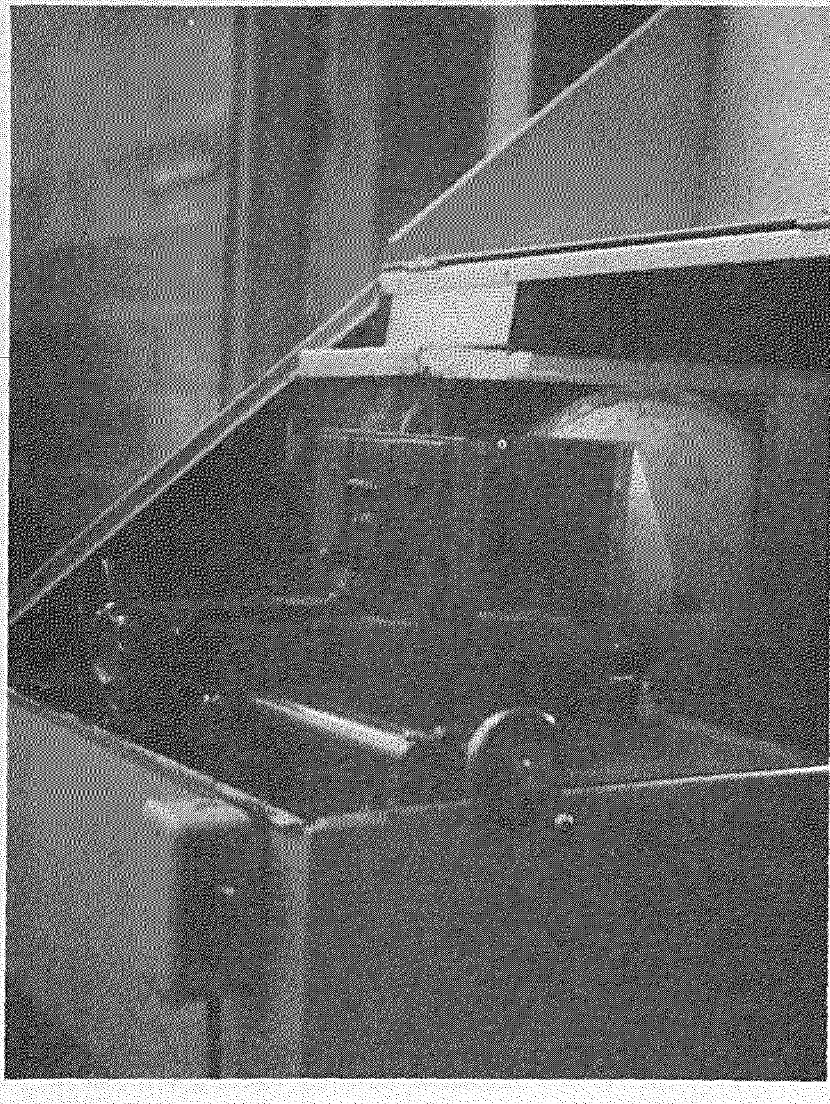


Figure 2. Vise-Type Specimen Carriage For Diamond Blade Slab Saw.

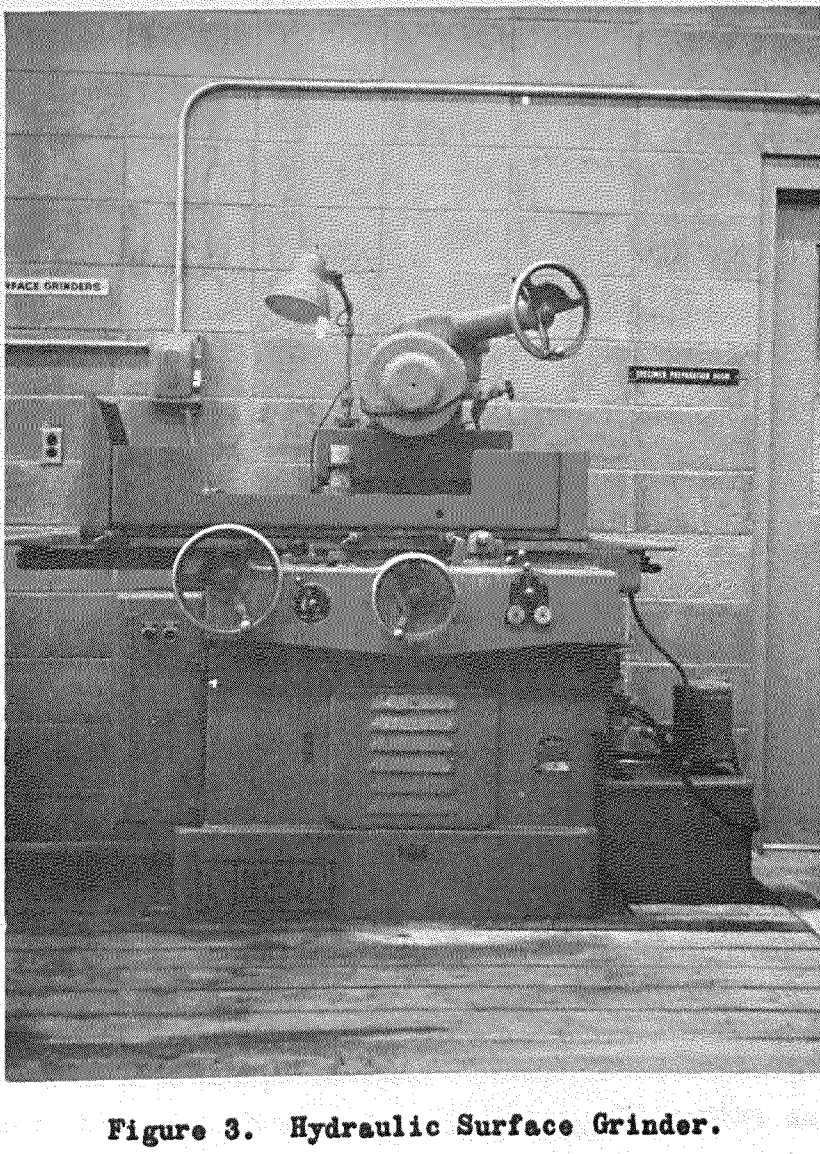


Figure 3. Hydraulic Surface Grinder.

Bulk Density

Bulk densities were determined according to U. S. Army Engineer Waterways Experiment Station, Concrete Division "T-2 Method of Determining Bulk Density of Rock Cores." The test procedure consisted of:

(a) wash the core to remove dust and other coatings from the specimen

(b) air dry the specimen to constant weight, and weigh air-dried specimen to nearest 0.1 gram

(c) determine volume of specimen by liquid displacement in a pycnometer chamber (Figure 4) containing distilled water

(d) calculate the density of the core in the air-dried condition from the following formula:

$$G_o = \frac{W_o}{V_o}$$

where

G_o = density of the air-dried core

W_o = weight of the air-dried core in grams

V_o = volume of the core in cubic centimeters.

Temperature of the distilled water in the pycnometer chamber was taken into account when the volumes of the specimens were determined.

In this investigation, densities were computed from air-dried specimens rather than oven-dried specimens to avoid possible changes in physical properties due to oven-drying as have been observed in several previous studies. Obert (9), noted that oven-drying often produced pronounced and sometimes drastic changes in elastic constants, and that these changes were frequently permanent.

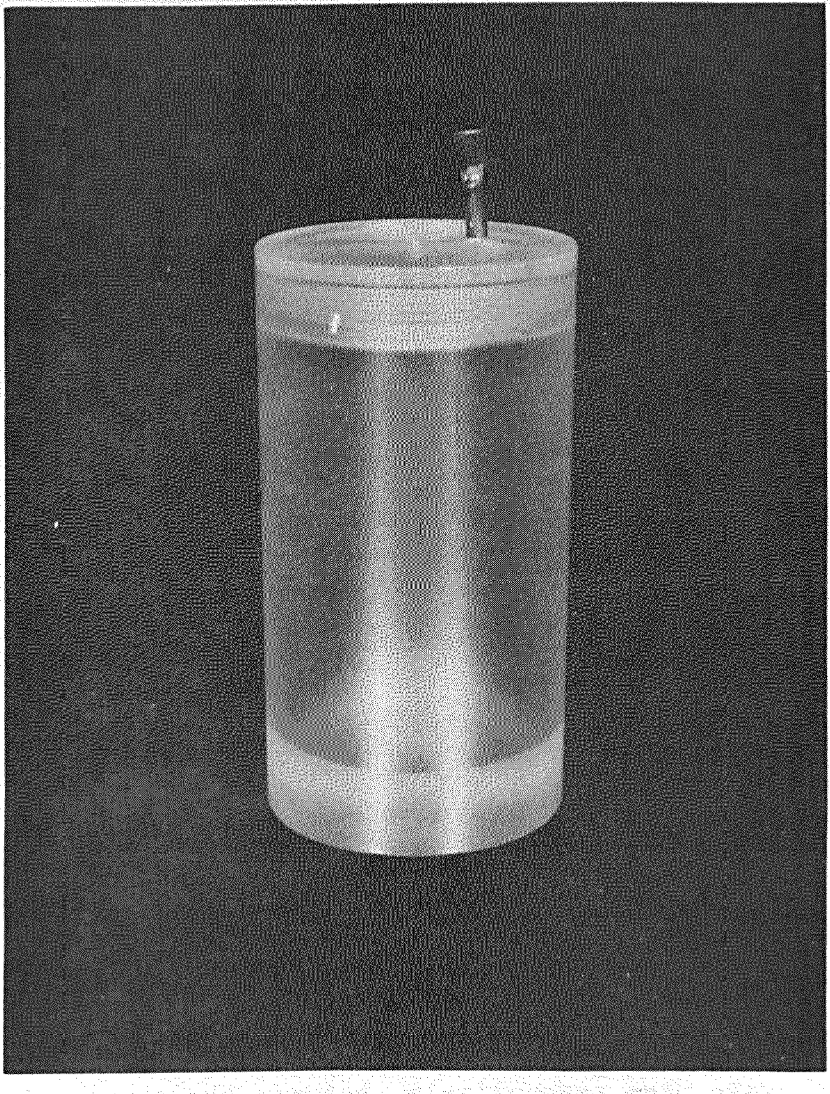


Figure 4. Pycnometer Chamber.

Ultrasonic Pulse Velocities

Ultrasonic pulse velocities were determined according to the ASTM proposed "Standard Method of Test for Laboratory Determination of Ultrasonic Pulse Velocities and Elastic Constants of Rock." This method is valid for determination of compressional and shear wave velocities in both isotropic and anisotropic media.

Barium titanate crystals and PZT-5A high capacitance lead-zirconate-titanate crystals were used to produce compressional and shear pulses, respectively. These pulses were produced by applying short duration, high voltage pulses to the appropriate crystals, resulting in compressional or shear pulses, whichever the case may be, being generated in the specimen. The high voltage pulses, when applied to the X-cut barium titanate crystal, caused the crystal to expand and contract yielding compressional stress pulses, which were transmitted to one end of the specimen. When applied to the Y-cut lead-zirconate-titanate crystal, the pulses caused the shear crystal to vibrate in a direction perpendicular to the axis of the core creating shear pulses which were transmitted to one end of the specimen. The arrival of the pulses at the other end of the specimen were noted by a companion crystal affixed to that end, which acted as a mechanical-electrical transducer and generated equivalent electrical pulses. Pureline white petroleum jelly and phenyl salicylate were used respectively, between the compressional transducers and the rock specimens, and between the shear transducers and the rock specimens.

These electrical signals were recorded on an oscilloscope (Figure 5) as stationary wave forms, which allowed rather accurate

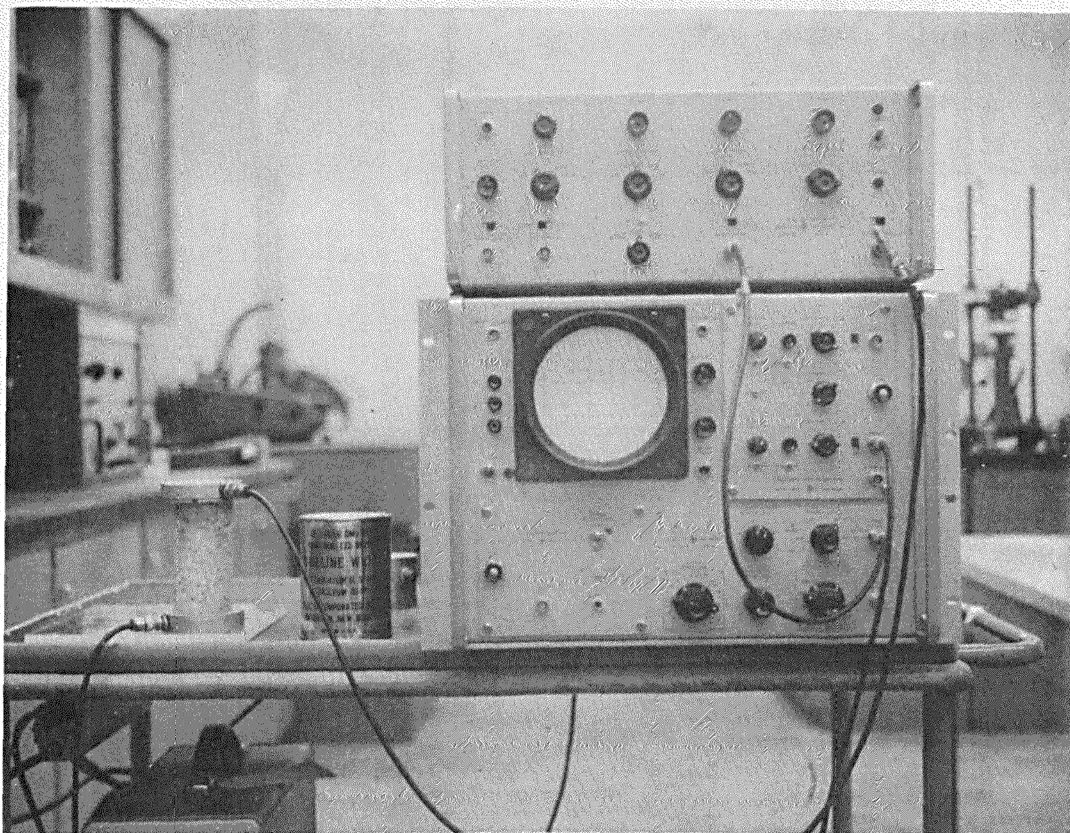


Figure 5. Equipment For Measuring Ultrasonic Pulse Velocities.

measurement of the time of travel of the pulses through the individual specimens. Stationary wave forms, as displayed on a Hewlett-Packard model 1780-A oscilloscope, were photographed (Figure 6) and pulse travel times read directly from the time marked photographs. These times were corrected to eliminate error due to pulse travel time through the transducer leads, transducers, and transducer-specimen connection materials (petroleum jelly or phenyl salicylate), thus, yielding pulse travel times through the rock core specimens above. Compressional and shear velocities were then determined from

$$V_p = \frac{L}{t_p} \quad \text{and} \quad V_s = \frac{L}{t_s}$$

where

V_p = compressional pulse velocity

V_s = shear pulse velocity

t_p = travel time of the compressional pulse through the specimen alone

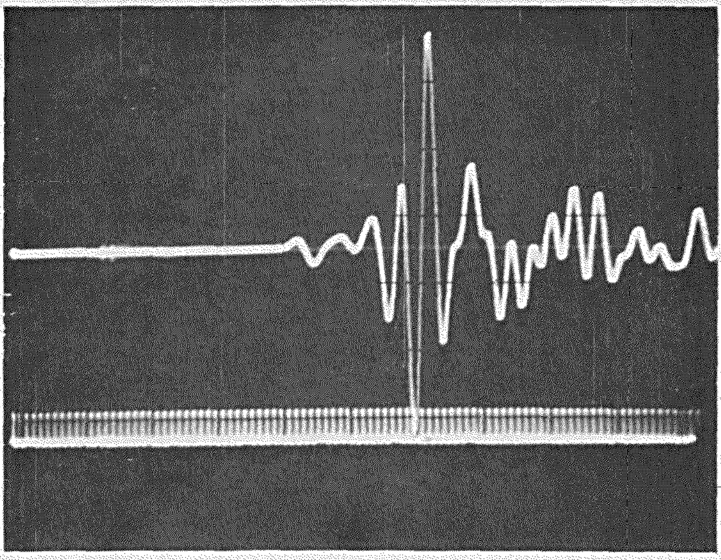
t_s = travel time of the shear pulse through the specimen alone

L = length of the specimen.

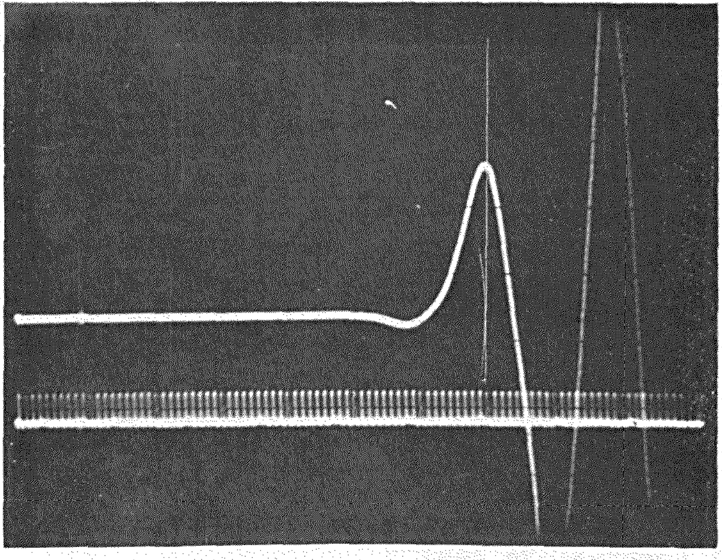
All compressional and shear pulse velocities determined in this investigation were measured with zero load on the specimens.

Static Axial Stress-Strain Measurements

To determine axial static stress-strain relations, Baldwin-Lima-Hamilton SR-4, Type A3-S-6, electrical resistance strain gages were affixed vertically to opposite sides of each specimen. The gages were located in a manner such that the midpoint of the



Shear Pulse



Compressional Pulse

Figure 6. Typical Photographs of Ultrasonic Wave-Forms As Displayed on Hewlett-Packard Oscilloscope.

resistance segment was at midheight of each specimen. The gage length was 13/16 inches, such that no portion would be effected by the nonuniform stress distributions noted by Fairhurst (5) to exist over the upper and lower 1/12 length of each specimen, i.e., the uppermost and lowermost 1/3 to 1/2 inches for all specimens used in this study.

All gages were bonded directly to the rock specimens by using SR-4 cement, a fast drying nitro-cellulose cement manufactured by Baldwin-Lima-Hamilton for the express purpose of application of SR-4 bonded strain gages. Prior to application of the cement, specimen surfaces were cleaned to remove substances such as oil or dust which might impede development of a secure bond between the specimen and gage. A thin coat of cement was then applied both to the specimen and to the gage, after which the gage was mounted under moderate pressure and allowed to dry for 24 hours.

To determine stress-strain relations, the two gages were wired in series resulting in an output of the average strain registered by the two gages. Stress and strain were continuously plotted during the uniaxial compressive test by using a Moseley Autograf x-y recorder. A photograph of the recording equipment is given in Figure 7.

Uniaxial Compressive Test

All specimens were subjected to static compressive loading to determine axial stress-strain relations, as previously mentioned, and to determine ultimate uniaxial compressive strengths.

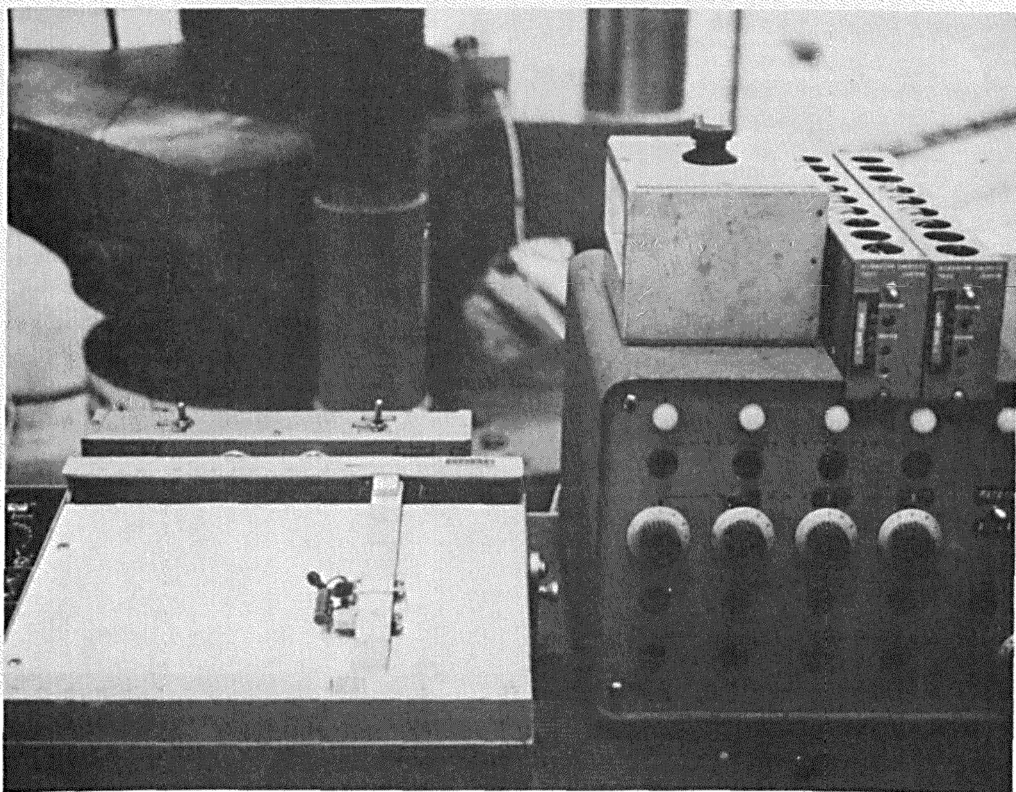


Figure 7. Moseley Autograf, x-y Recorder and Other Stress-Strain Recording Equipment

A 440,000-pound universal, Baldwin hydraulic testing machine was used for loading the specimens. A photograph of this machine is given as Figure 8.

This test was conducted according to the ASTM proposed Standard Method of Test for Unconfined Compressive Strength of Rock Core Specimens. All specimens were carefully aligned so that the axis of each core tested was coincident with the center of thrust of the spherically seated bearing block. An initial seating load of approximately 100-200 pounds was applied very slowly while the spherical seated bearing block was adjusted. All tests were conducted at a loading rate of 35 ± 15 psi per second (constant for a particular specimen) so that catestrophic failure occurred within 5 to 15 minutes of commencement of loading. As noted by the proposed standard, such a rate of load should provide values of ultimate uniaxial compressive strength which are relatively free from the effects of rapid loading.

Ultimate uniaxial compressive strengths were calculated by dividing the maximum load carried by the specimen during the test by the average initial cross-sectional area of the specimen determined as suggested in the ASTM proposed standard. All strengths were expressed to the nearest 10 psi.

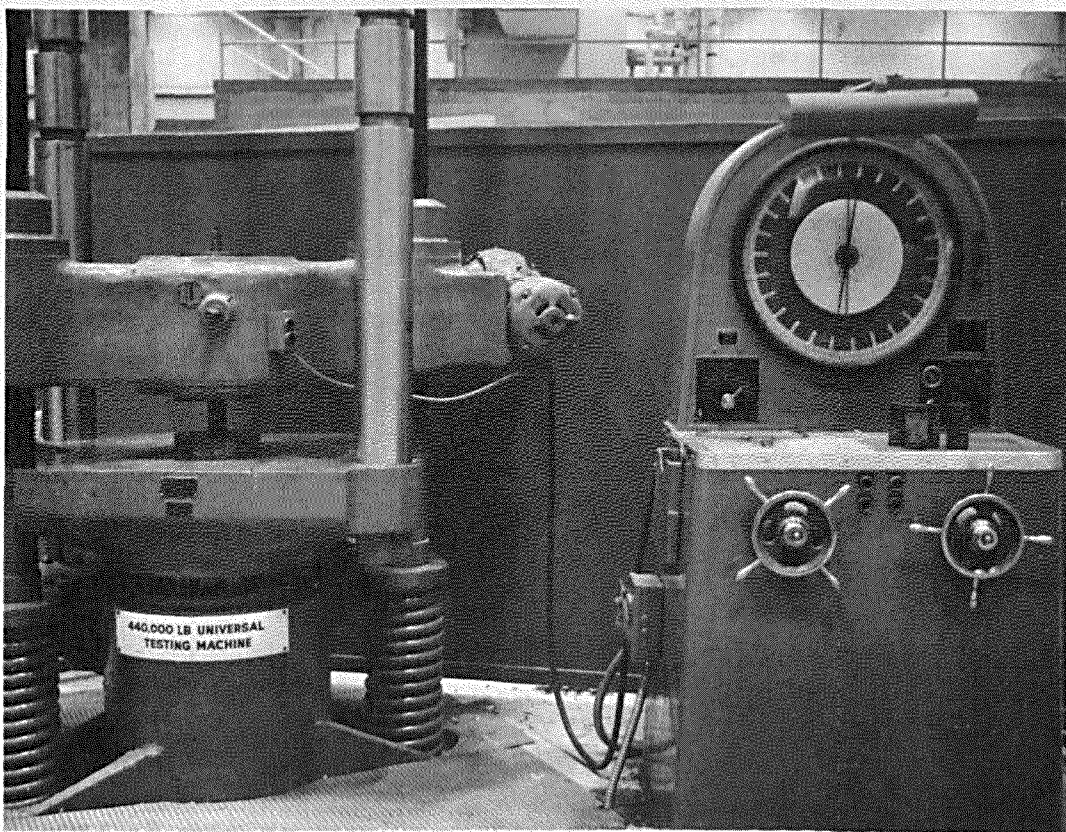


Figure 8. Baldwin 440,000-pound Universal Testing Machine

CHAPTER 3

PRESENTATION AND DISCUSSION OF RESULTS

General

Physical properties of the various granite and tonalite specimens tested were determined according to the procedures discussed in Chapter 2 and are presented in tabular form in Tables 1 and 2.

The ~~static values~~ of Young's moduli are tangent moduli of elasticity and were computed at 50 percent of ultimate uniaxial compressive strength. Static Young's moduli were determined for a minimum of six specimens from each drill site represented (ten sites), thus exceeding the optimum number of four specimens and minimum number of three recommended by the Bureau of Mines (1) for adequate evaluation of this particular property within a representative group of specimens.

Ultrasonic elastic constants were computed from individual values of density, ultrasonic compressional pulse velocity, and ultrasonic shear pulse velocity which were determined for each specimen by procedures as discussed in Chapter 2. The equations used in the computation of ultrasonic elastic constants are as follows:

(1) $$E_{dyn} = \frac{\rho V_s^2(3V_p^2 - 4V_s^2)}{V_p^2 - V_s^2}$$

(2) $$G_{dyn} = \rho V_s^2$$

TABLE 1

Physical Property Test Results

Specimen No.	Petrographic Description ( )*	Ultimate Uniaxial Compressive Strength psi	Static Young's Modulus psi x 10^{-6}	Ultrasonic Pulse Velocities fps Compressional	Shear
1a	Tonalite (a)	29,200	10.0	16,160	9,190
2a	Tonalite (a)	24,400	—**	15,240	8,830
3a	Tonalite (a)	25,200	—**	16,200	8,860
4a	Tonalite (a)	23,000	9.6	16,240	8,830
5a	Tonalite (a)	27,400	10.0	16,160	9,120
6a	Tonalite (a)	24,600	9.3	14,180	8,550
7a	Tonalite (a)	29,800	10.0	15,960	8,950
8a	Tonalite (a)	29,600	10.0	16,090	9,080
1e	Tonalite (e)	22,500	7.4	15,650	8,570
2e	Tonalite (e)	21,700	7.8	15,400	8,050
3e	Tonalite (e)	17,800	7.6	15,180	8,570
4e	Tonalite (e)	20,400	6.9	12,900	7,670
5e	Tonalite (e)	14,200	—**	14,790	8,030
6e	Tonalite (e)	20,500	6.9	12,860	7,670
7e	Tonalite (e)	15,400	6.1	14,830	8,090
8e	Tonalite (e)	17,500	6.9	17,860	9,350
1f	Tonalite (f)	22,900	8.3	15,900	8,690
2f	Tonalite (f)	24,000	8.3	14,590	8,590
3f	Tonalite (f)	24,200	8.1	13,540	8,260
4f	Tonalite (f)	24,300	7.8	13,430	8,070

*Corresponds to petrographic descriptions given in Chapter 2, pages 7-9.
**Static Young's moduli not determined for these specimens.

TABLE 1 (Cont'd)

Specimen No.	Petrographic Description ( )*	Ultimate Uniaxial Compressive Strength psi	Static Young's Modulus psi x 10^{-6}	Ultrasonic Pulse Velocities fps	
				Compressional	Shear
5f	Tonalite (f)	23,600	8.6	14,880	8,510
6f	Tonalite (f)	22,600	7.8	16,240	8,990
7f	Tonalite (f)	24,600	8.3	14,710	8,450
8f	Tonalite (f)	24,500	--**	13,510	7,760
1d	Tonalite (d)	36,400	11.4	20,180	10,570
2d	Tonalite (d)	47,200	11.6	20,120	10,590
3d	Tonalite (d)	20,800	9.8	19,050	9,900
4d	Tonalite (d)	43,200	11.6	20,790	10,700
5d	Tonalite (d)	45,500	11.6	21,160	10,970
6d	Tonalite (d)	43,900	11.9	20,510	10,620
7d	Tonalite (d)	45,700	11.9	20,460	10,650
1i	Tonalite (i)	9,800	4.2	12,590	6,560
2i	Tonalite (i)	18,900	5.3	12,340	6,790
3i	Tonalite (i)	15,100	4.7	12,230	6,650
4i	Tonalite (i)	17,800	5.4	12,750	6,730
5i	Tonalite (i)	12,500	4.3	12,610	7,050
6i	Tonalite (i)	19,000	5.6	13,240	7,080
7i	Tonalite (i)	12,300	4.5	12,860	6,950
8i	Tonalite (i)	12,900	4.4	13,020	6,890

*Corresponds to petrographic descriptions given in Chapter 2, pages 7-9.
**Static Young's moduli not determined for these specimens.

TABLE 1 (Cont'd)

Specimen No.	Petrographic Description ( )*	Ultimate Uniaxial Compressive Strength psi	Static Young's Modulus psi x 10^{-6}	Ultrasonic Pulse Velocities fps Compressional	Ultrasonic Pulse Velocities fps Shear
1c	Granite (c)	34,000	9.4	17,430	9,290
2c	Granite (c)	31,100	8.6	16,360	8,750
3c	Granite (c)	34,600	9.3	18,830	9,340
4c	Granite (c)	32,800	9.4	18,130	9,560
5c	Granite (c)	33,900	9.6	19,340	9,860
6c	Granite (c)	32,300	9.8	18,100	9,530
7c	Granite (c)	33,900	9.6	17,430	9,200
8c	Granite (c)	25,600	10.0	18,120	9,400
1g	Granite (g)	23,600	9.6	17,900	9,530
2g	Granite (g)	21,100	9.6	18,620	9,210
3g	Granite (g)	17,100	--**	18,040	9,690
4g	Granite (g)	25,800	10.2	17,860	9,450
5g	Granite (g)	23,000	10.0	18,350	9,630
6g	Granite (g)	19,000	10.3	17,800	9,720
7g	Granite (g)	26,500	9.6	18,270	9,580
8g	Granite (g)	20,800	--**	18,510	9,820
1h	Granite (h)	18,400	--**	17,870	9,220
2h	Granite (h)	21,900	9.3	17,790	9,110
3h	Granite (h)	23,100	9.4	19,070	9,640
4h	Granite (h)	22,200	8.3	18,370	9,540

*Corresponds to petrographic descriptions given in Chapter 2, pages 7-9.
**Static Young's moduli not determined for these specimens.

TABLE 1 (Cont'd)

Specimen No.	Petrographic Description ( )*	Ultimate Uniaxial Compressive Strength psi	Static Young's Modulus psi x 10^{-6}	Ultrasonic Pulse Velocities fps Compressional	Shear
5h	Granite (h)	22,000	—**	18,530	9,630
6h	Granite (h)	22,600	9.3	17,370	8,970
7h	Granite (h)	24,300	9.4	17,900	9,180
8h	Granite (h)	23,400	9.4	18,320	8,930
1b	Granite (b)	15,300	5.0	10,950	7,070
2b	Granite (b)	16,800	6.9	11,390	7,000
3b	Granite (b)	14,700	6.0	11,700	7,290
4b	Granite (b)	16,900	5.8	10,940	7,310
5b	Granite (b)	14,700	6.0	10,880	7,490
6b	Granite (b)	15,000	5.4	9,870	6,970
7b	Granite (b)	17,600	5.7	10,070	6,500
8b	Granite (b)	14,900	5.4	11,100	7,370
1j	Granite (j)	13,100	7.6	17,180	9,260
2j	Granite (j)	15,000	8.3	16,780	8,660
3j	Granite (j)	13,000	7.4	16,880	8,500
4j	Granite (j)	13,500	7.6	17,090	8,670
5j	Granite (j)	13,400	8.3	18,480	9,340
6j	Granite (j)	13,100	7.8	17,180	8,570
7j	Granite (j)	11,600	7.6	18,130	9,070
8j	Granite (j)	12,400	7.4	17,070	8,670

*Corresponds to petrographic descriptions given in Chapter 2, pages 7-9.
**Static Young's moduli not determined for these specimens.

TABLE 2

Computed Ultrasonic Properties

Specimen No.	Ultrasonic Moduli, psi x 10^{-6}			Ultrasonic Poisson's Ratio
	Young's	Bulk	Shear	
1a	7.6	5.3	3.0	0.26
2a	6.9	4.6	2.8	0.25
3a	7.2	5.6	2.8	0.29
4a	7.2	5.7	2.8	0.29
5a	7.5	5.4	3.0	0.27
6a	6.3	3.7	2.6	0.21
7a	7.3	5.3	2.9	0.27
8a	7.4	5.3	2.9	0.27
1e	7.1	5.5	2.8	0.29
2e	6.4	5.6	2.4	0.31
3e	7.0	5.0	2.8	0.27
4e	5.4	3.3	2.2	0.23
5e	6.2	4.9	2.4	0.29
6e	5.4	3.2	2.2	0.22
7e	6.3	4.9	2.4	0.29
8e	8.6	7.6	3.3	0.31
1f	7.1	5.6	2.8	0.29
2f	6.9	4.2	2.7	0.23
3f	6.0	3.4	2.5	0.20
4f	5.8	3.4	2.4	0.22
5f	6.7	4.6	2.6	0.26
6f	7.6	5.8	3.0	0.28
7f	6.6	4.4	2.6	0.25
8f	5.5	3.7	2.2	0.25

TABLE 2 (Cont'd)

Specimen No.	Ultrasonic Moduli, psi x 10^{-6} Young's	Bulk	Shear	Ultrasonic Poisson's Ratio
1d	11.2	9.9	4.3	0.31
2d	11.2	9.8	4.3	0.31
3d	9.9	9.0	3.8	0.32
4d	11.7	10.8	4.5	0.32
5d	12.1	11.0	4.6	0.32
6d	11.4	11.4	4.4	0.32
7d	11.6	10.4	4.4	0.31
1i	4.0	3.6	1.5	0.31
2i	4.2	3.2	1.6	0.28
3i	4.0	3.2	1.6	0.29
4i	4.2	3.6	1.6	0.31
5i	4.5	3.3	1.8	0.27
6i	4.6	3.9	1.8	0.30
7i	4.4	3.6	1.7	0.29
8i	4.4	3.8	1.7	0.31
1c	8.0	6.7	3.1	0.30
2c	7.1	5.9	2.7	0.30
3c	9.5	8.0	3.4	0.31
4c	8.5	7.3	3.2	0.31
5c	9.2	8.7	3.5	0.32
6c	8.4	7.3	3.2	0.31
7c	7.8	6.8	3.0	0.31
8c	8.2	7.4	3.1	0.32
1g	8.3	7.0	3.2	0.30
2g	7.8	8.2	3.0	0.34
3g	8.6	7.0	3.3	0.30
4g	8.2	7.0	3.1	0.31

TABLE 2 (Cont'd)

Specimen No.	Ultrasonic Moduli, psi x 10^{-6} Young's	Bulk	Shear	Ultrasonic Poisson's Ratio
5g	8.5	7.5	3.3	0.31
6g	8.6	6.7	3.3	0.29
7g	8.4	7.4	3.2	0.31
8g	8.8	7.5	3.4	0.30
1h	8.2	7.6	3.1	0.32
2h	8.0	7.6	3.0	0.32
3h	9.0	8.8	3.4	0.33
4h	8.7	7.9	3.3	0.32
5h	8.9	8.0	3.4	0.32
6h	7.7	7.1	2.9	0.32
7h	8.1	7.6	3.1	0.32
8h	7.8	8.4	2.9	0.34
1b	4.1	1.9	1.8	0.14
2b	4.2	2.3	1.8	0.20
3b	4.5	2.4	1.9	0.18
4b	4.2	1.7	1.9	0.10
5b	4.2	1.6	2.0	0.05
6b	3.5	1.2	1.7	0.01
7b	3.5	1.6	1.5	0.14
8b	4.3	1.8	1.9	0.11
1j	8.1	6.6	3.1	0.30
2j	7.1	6.6	2.7	0.32
3j	6.9	6.8	2.6	0.33
4j	7.1	6.9	2.7	0.33
5j	8.4	8.2	3.2	0.33
6j	7.1	7.2	2.7	0.33
7j	8.0	8.0	3.0	0.33
8j	7.3	7.0	2.7	0.33

(3) $K_{dyn} = \dfrac{\rho(3V_p^2 - 4V_s^2)}{3}$

(4) $\nu_{dyn} = \dfrac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}$

where

E_{dyn} = ultrasonic Young's modulus of elasticity in psi

G_{dyn} = ultrasonic shear modulus or modulus of rigidity in psi

K_{dyn} = ultrasonic bulk modulus in psi

ν_{dyn} = ultrasonic Poisson's ratio

ρ = density in pound-second^2 per inch^4

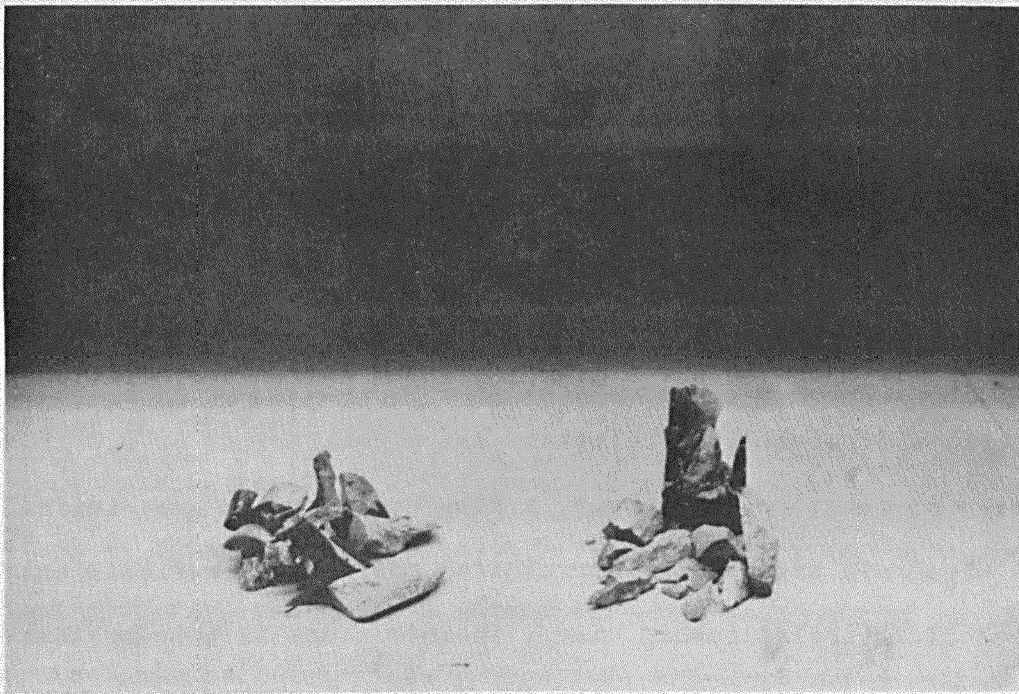
V_p = ultrasonic compressional pulse velocity in inches per second

V_s = ultrasonic shear pulse velocity in inches per second.

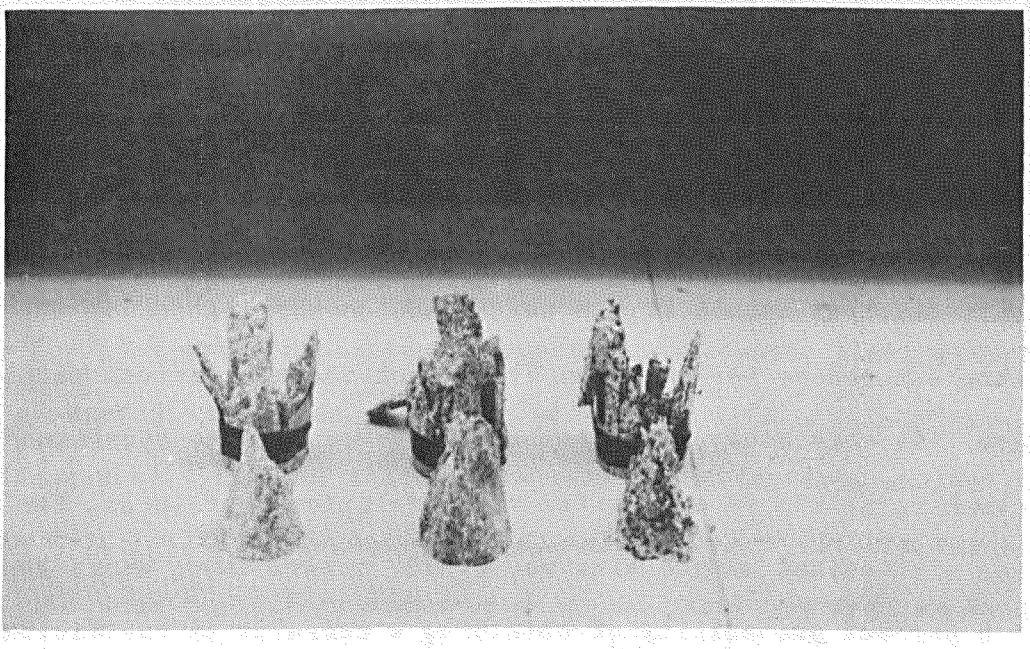
The number of specimens for which these constants were determined in all cases exceeded both the minimum and optimum number of tests per group (3 and 6, respectively) recommended by the Bureau of Mines (1).

Typical modes of failure exhibited by the seventy-nine rock core specimens tested in uniaxial compression are illustrated in the photographs in Figure 9. Explosive type failures yielding the fragments illustrated in Figure 9(a) were typical of failures in the stronger tonalites, i.e., those yielding ultimate uniaxial compressive strengths greater than 35,000 psi. The conical type failure surfaces illustrated in Figure 9(b) were typical of the nature of failure exhibited by the remainder of the specimens tested.

In order to evaluate the linear degree of association between the various pairs of physical properties of interest in this investigation, correlation coefficients were computed for each of the



a. Typical Explosive Type Failure Surfaces



b. Typical Conical Type Failure Surfaces

Figure 9. Typical Failures of Rock Cores in Uniaxial Compression

groups of data. A least-squares line was also fitted to each data group, the intention being to give a visual representation of the degree of linear correlation between the particular physical properties of interest.

The correlation coefficient (r) is a measure of the degree of interdependence between the particular variables under study, with a coefficient of 1.0 or -1.0 indicating a perfect association, i.e., a perfect straight line relation, and a coefficient of 0.0 indicating no relation whatsoever, a completely random association. The algebraic sign of the correlation coefficient reflects only the slope of the relationship, i.e., whether there is a trend toward increase or decrease in magnitude of one variable accompanying an increase in the magnitude of other variables.

Once the correlation coefficients for the various groups of data were determined, it remained to evaluate the significance of these correlations, i.e., determine the probability of getting a correlation coefficient as large as the one actually obtained from the statistical sample if, in actuality, no correlation of this nature existed in the universe from which the statistical sample was taken. In this study, the probability level used to determine the minimum magnitude of a significant correlation coefficient for a given statistical sample size was 0.995. Thus, there would be only a 0.5 percent probability of obtaining a correlation coefficient of a magnitude greater than or equal to the predetermined value from a statistical sample taken from a universe in which no correlation of this nature actually existed. A table of critical values for correlation coefficients corresponding to this chosen probability level and the various statistical sample sizes used in this study is presented as Appendix II.

The actual mathematical determination of the individual correlation coefficients and equations for least-squares lines was, for each data group, performed on a General Electric 400 computer.

Discussion of Correlations

The remaining portion of this chapter will consist of the presentation of scatter diagrams (data plots) representing the various physical property correlations attempted. For each pair of physical properties examined, four data groups were arranged and correlated. These groups were comprised as follows:

Group 1: All tonalite specimens tested from the Sierra Nevada Batholith, California.

Group 2: All tonalite specimens tested.

Group 3: All granite specimens tested.

Group 4: All specimens tested.

Thus, for each pair of physical properties discussed, there will be four scatter diagrams, one for each group.

The correlations and scatter diagrams resulting from analysis of the data yielded by specimens comprising Group 1 (Sierra Navada Batholith tonalites) were compared to those resulting from analysis of the data yielded by the specimens comprising Group 2 (all tonalites). The objective of this comparison was to evaluate the degree of scatter which might be attributed to variation in grain size alone within the particular rock type. Variation in percentage mineral composition and geologic history were kept to a practical minimum for the Group 1 data (all specimens come from three holes within very close proximity of each other) and, for the Group 2 data, were allowed to vary within the confines imposed by restriction to the one particular rock type (tonalite). Therefore, close similarity between the correlation coefficients and scatter diagrams yielded for the two groups of data would suggest, for the particular pair of variables under consideration, that variation in grain size was of primary importance in the determination of degree of scatter typical of the association between those two physical properties for that rock type. On the other hand, significant dissimilarity in nature of the physical property correlations and correlation coefficients (i.e., a larger amount of scatter and lesser degree of linear association for the Group 2 data than for the Group 1 data) would indicate, for the particular pair of physical properties being examined, that variation in grain size, as opposed to variation in percentage mineral composition and geologic history as confined to the limits imposed by the particular rock type, was of lesser significance in the determination of the degree of scatter characteristic of the particular rock property correlation in question.

The correlations and scatter diagrams resulting from analysis of the data yielded by specimens comprising Groups 2 and 3 were compared to those resulting from analysis of the data yielded by specimens comprising Group 4 (all specimens in Groups 2 and 3 combined), the objective being to evaluate the effects of minimal variation in rock type on the nature of physical property correlations obtained for statistical data samples involving more than one igneous rock type. As data Groups 2 and 3 represented individual rock types (tonalite and granite, respectively) while data Group 4 represented both rock types, significant differences in the quality and orientation of the correlations determined for the three data groups should indicate the effects of slight variation in rock type on the nature of the resulting physical property correlations. Moreover, since the granites and tonalites involved in this investigation were relatively homogeneous and isotropic intrusive igneous rocks, and since the percentage mineral compositions of the two rock types are not extremely removed from one another (11), the rock property correlations determined for the data comprising Group 4 should indicate a reasonable maximum degree of linear association and minimum degree of scatter to be expected for the particular pairs of physical properties examined and for a statistical data sample which includes specimens representing more than one rock type.

C_0 Versus Ultrasonic Pulse Velocities (V_p and V_s). Scatter diagrams developed to illustrate the relationships between uniaxial compressive strength and ultrasonic compressional pulse velocity are presented in Figures 10 through 13. Figures 14 through 17 graphically illustrate the relationships found to exist between ultimate uniaxial compressive strength and ultrasonic shear pulse velocity as determined in this investigation.

The degrees of correlation characteristic of these two pairs of physical properties (C_0 versus V_p and C_0 versus V_s) were noticeably higher for the data yielded by the tonalite specimens alone than for the data yielded by the granite specimens alone. In particular, the

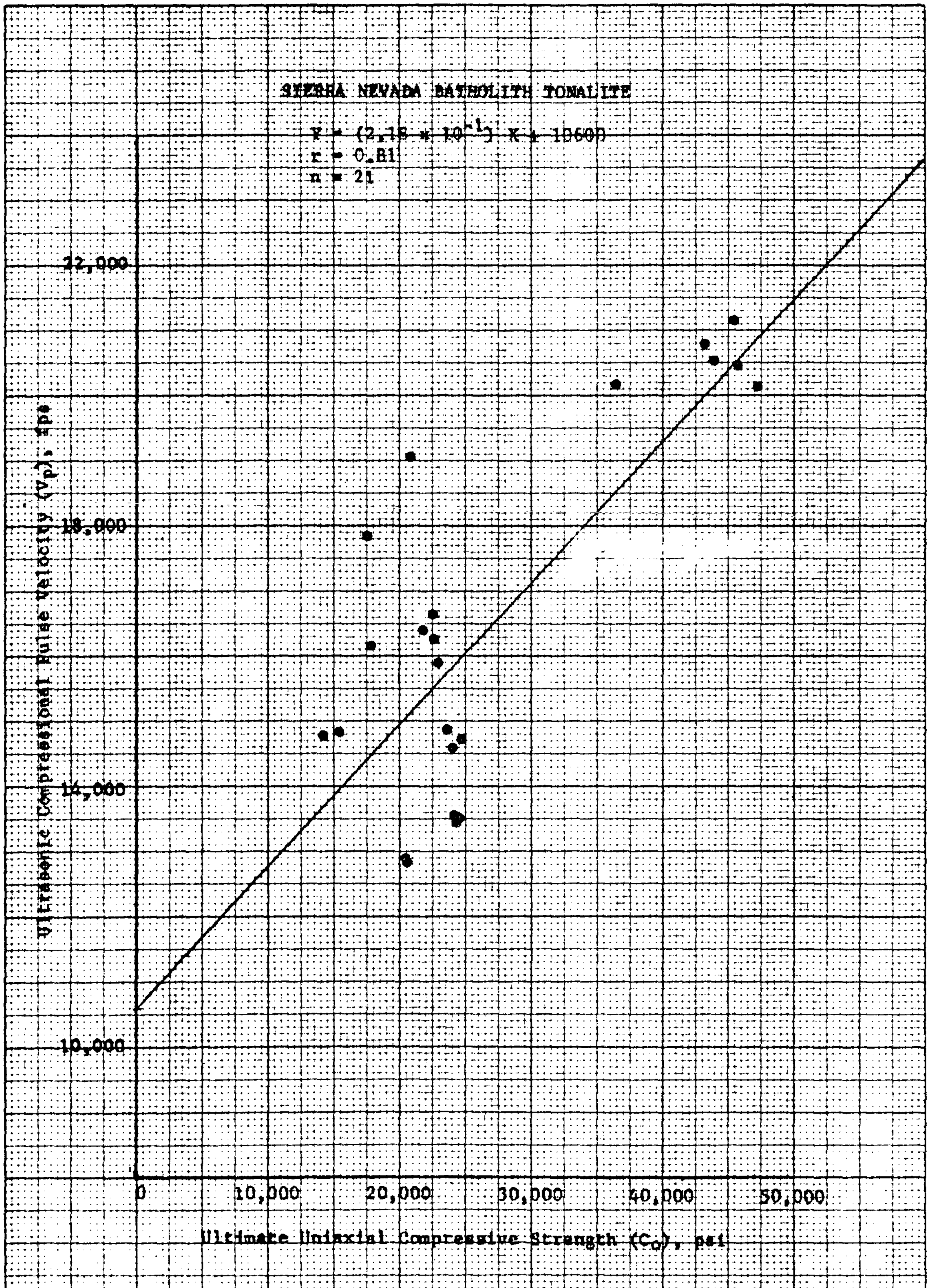
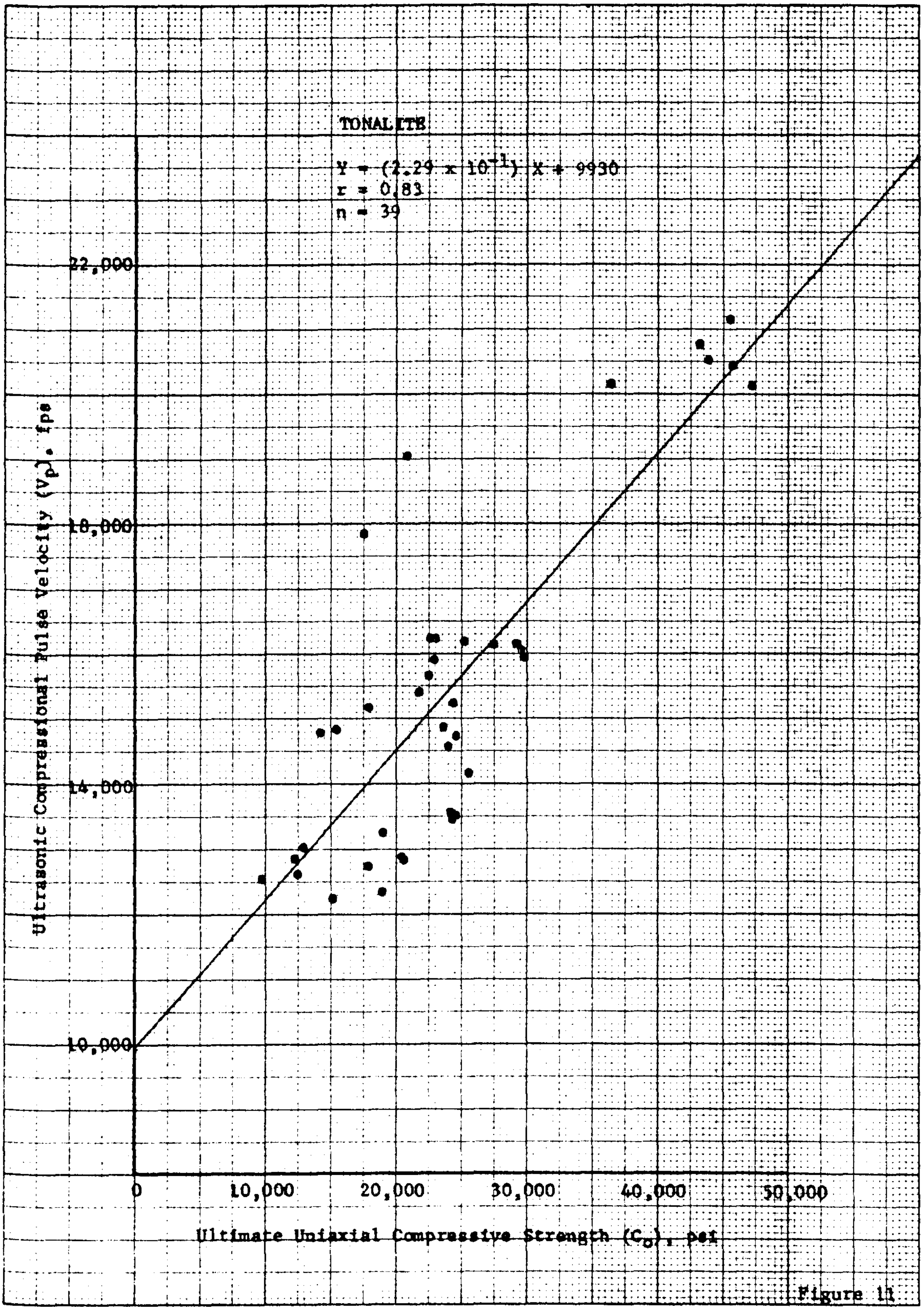
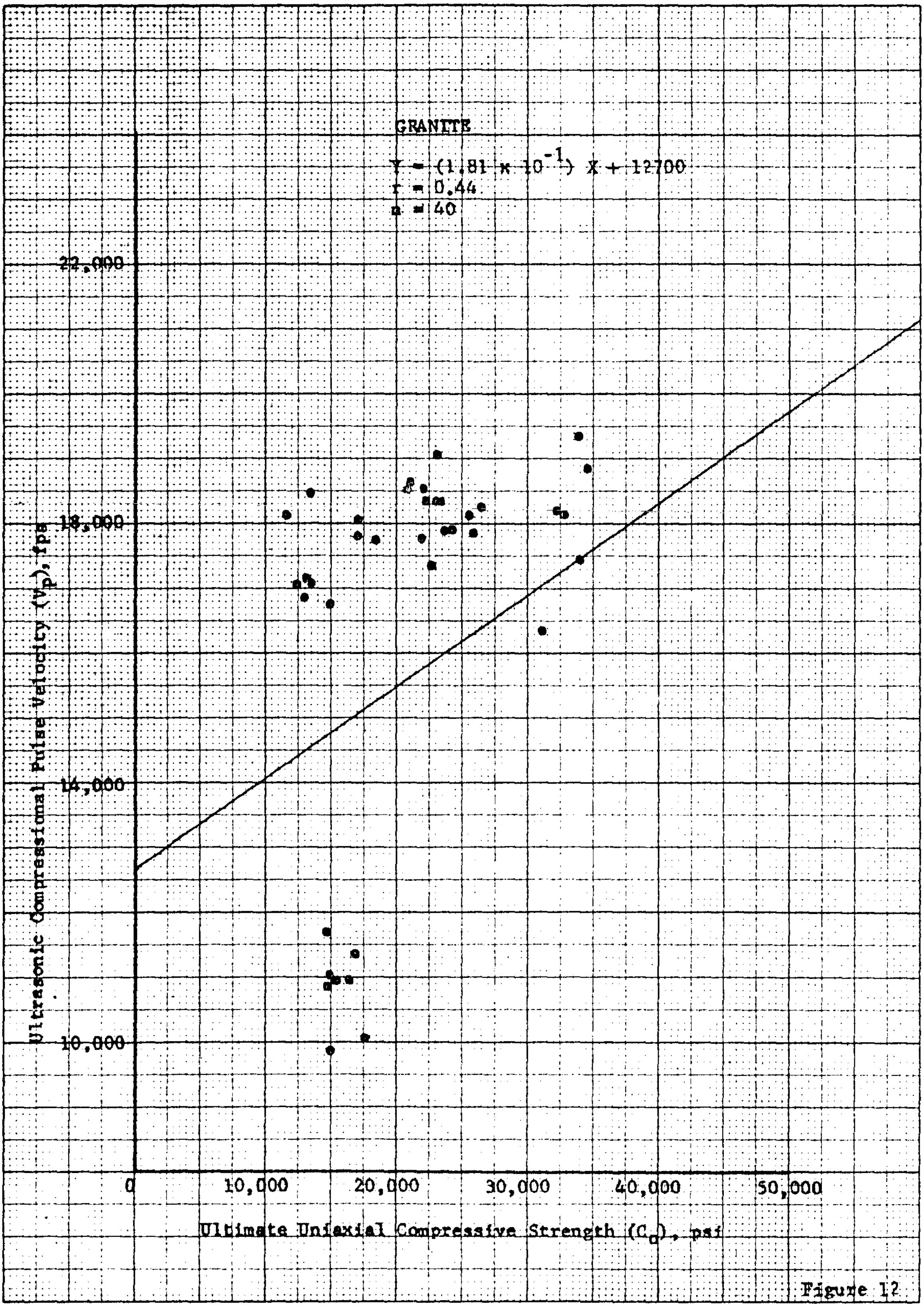

SIERRA NEVADA BATHOLITH TONALITE
Y = (2.18 x 10^-1) X + 10600
r = 0.81
n = 21
22,000
18,000
14,000
10,000
Ultrasonic Compressional Pulse Velocity (Vp), fps
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (Co), psi

Figure 10



TONALITE
Y = (2.29 x 10^-1) X + 9930
r = 0.83
n = 39
22,000
18,000
14,000
10,000
Ultrasonic Compressional Pulse Velocity (Vp), fps
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (Co), psi

Figure 11



GRANITE
Y = (1.81 x 10^-1) X + 12700
r = 0.44
n = 40
22,000
18,000
14,000
10,000
Ultrasonic Compressional Pulse Velocity (Vp), fps
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (Cu), psi

Figure 12

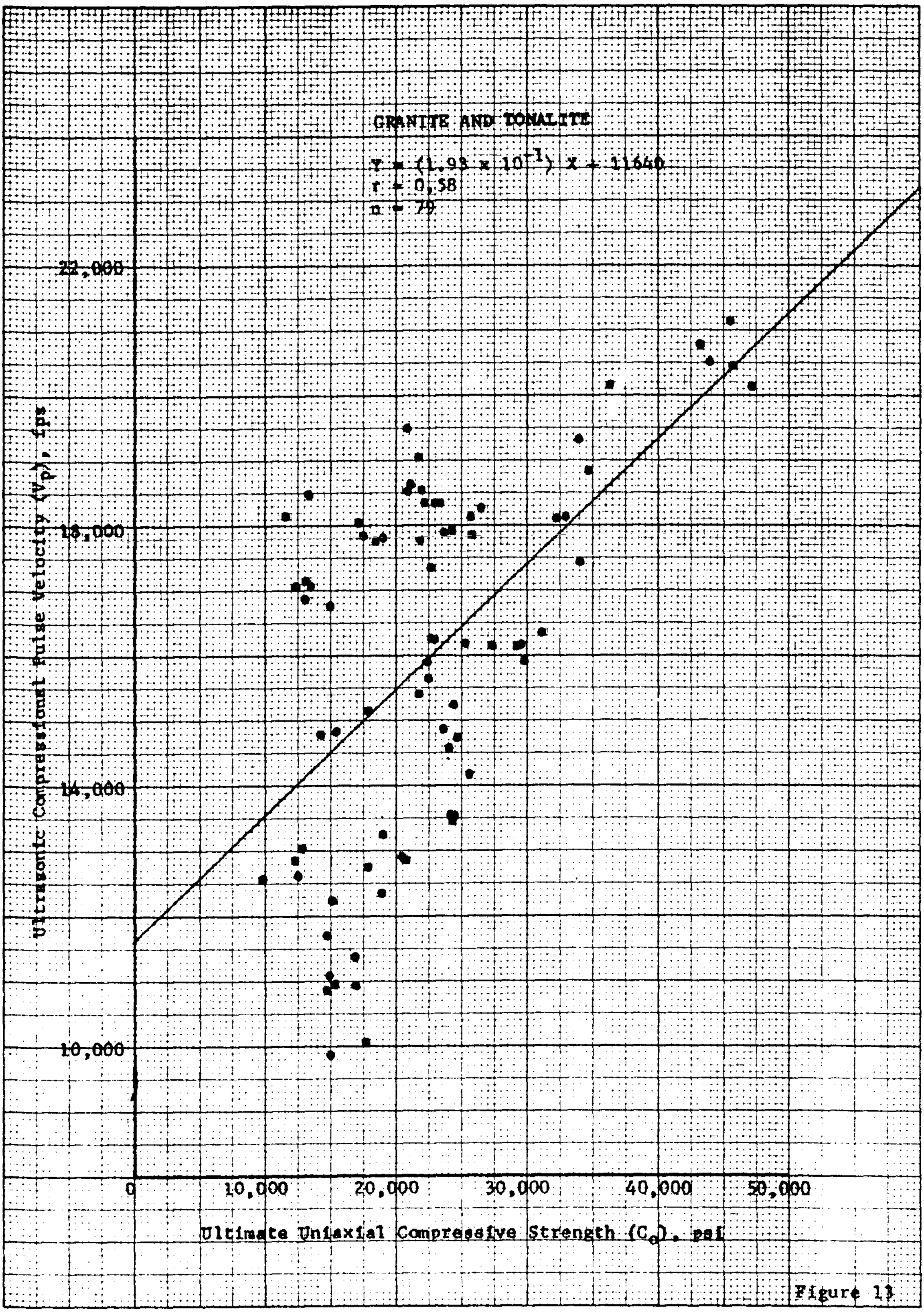
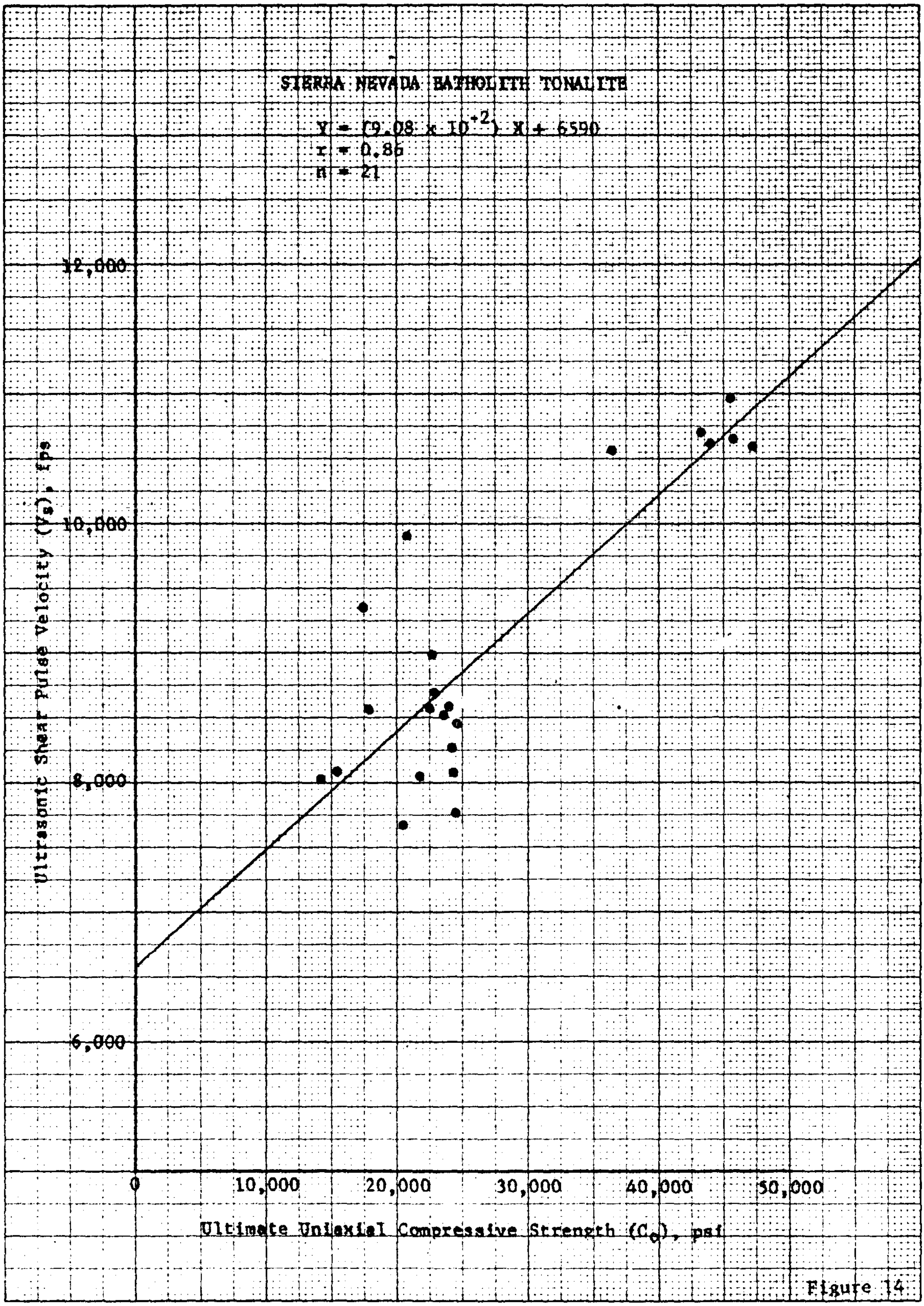
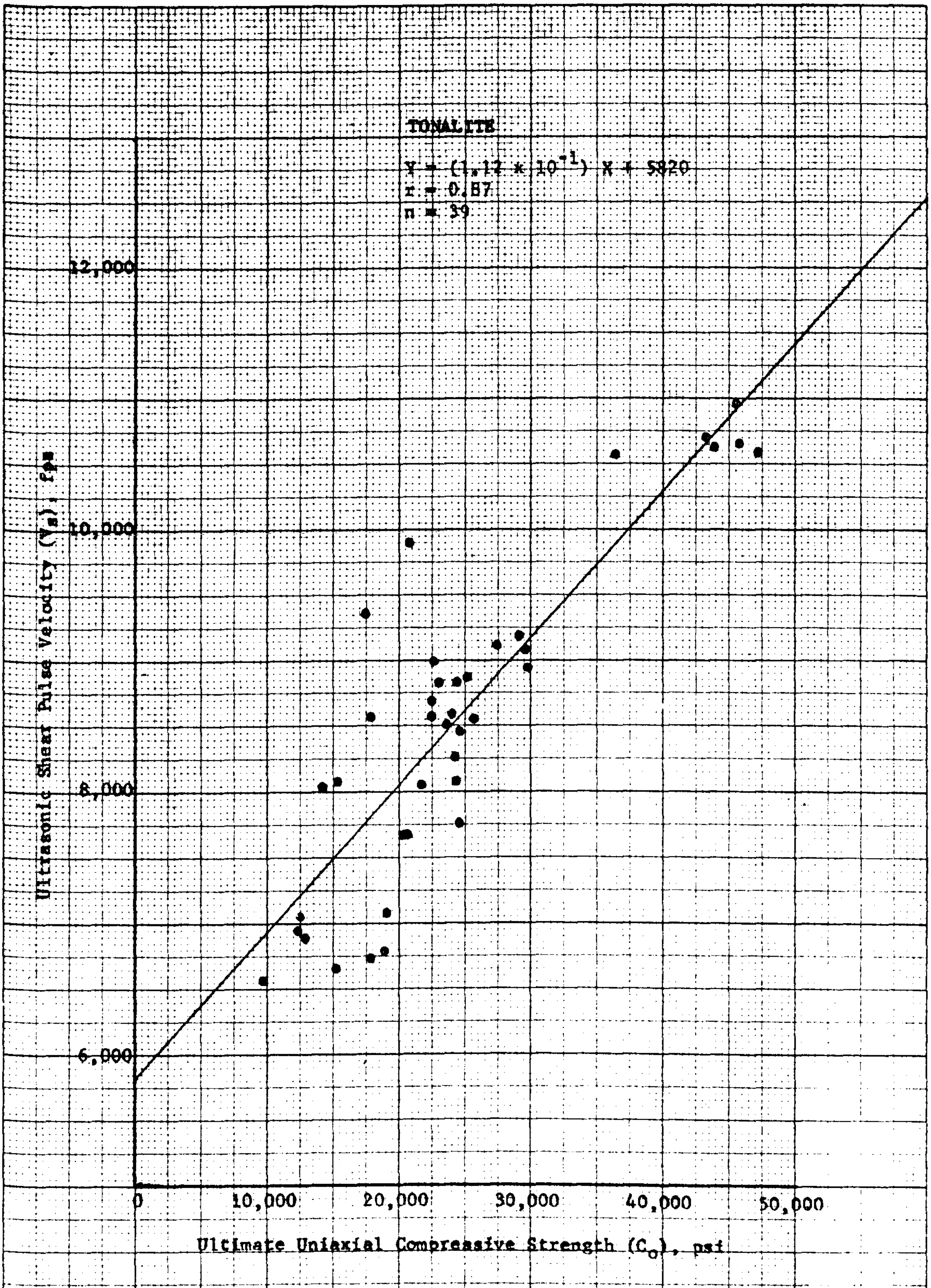

GRANITE AND TONALITE
Y = (1.93 x 10^-1) X + 11640
r = 0.58
n = 79
22,000
18,000
14,000
10,000
Ultrasonic Compressional Pulse Velocity (Vp), fps
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (Co), psi

Figure 13



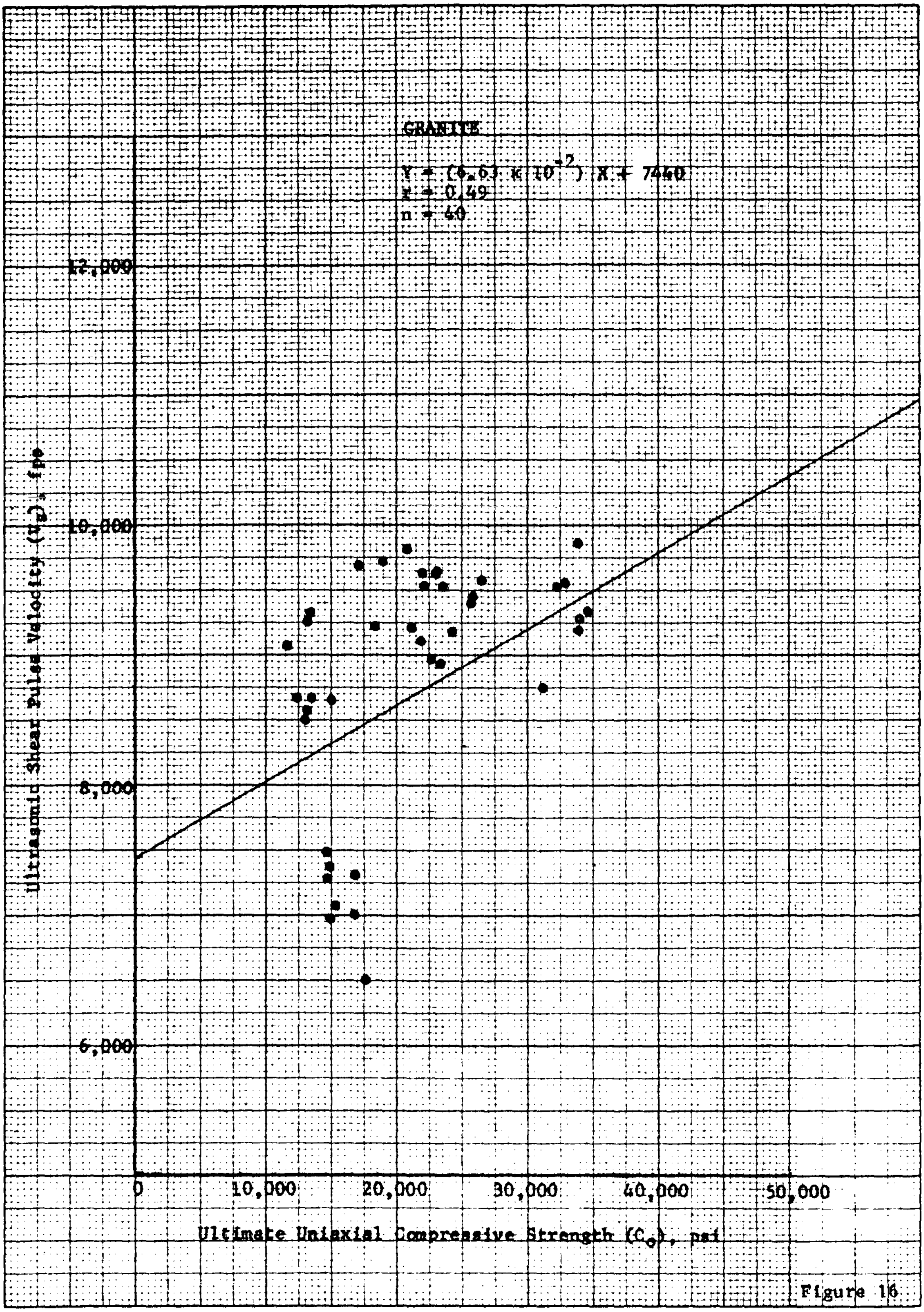
SIERRA NEVADA BATHOLITH TONALITE
Y = (9.08 x 10^-2) X + 6590
r = 0.86
n = 21
12,000
10,000
8,000
6,000
Ultrasonic Shear Pulse Velocity (Vs), fps
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (Co), psi

Figure 14



TONALITE
Y = (1.12 x 10^-1) X + 5820
r = 0.87
n = 39
12,000
10,000
8,000
6,000
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (Co), psi
Ultrasonic Shear Pulse Velocity (Vs), fps

Figure 15



GRANITE
Y = (6.63 x 10^-2) X + 7440
r = 0.49
n = 40
12,000
10,000
8,000
6,000
Ultrasonic Shear Pulse Velocity (V_s), fps
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (C_o), psi

Figure 16

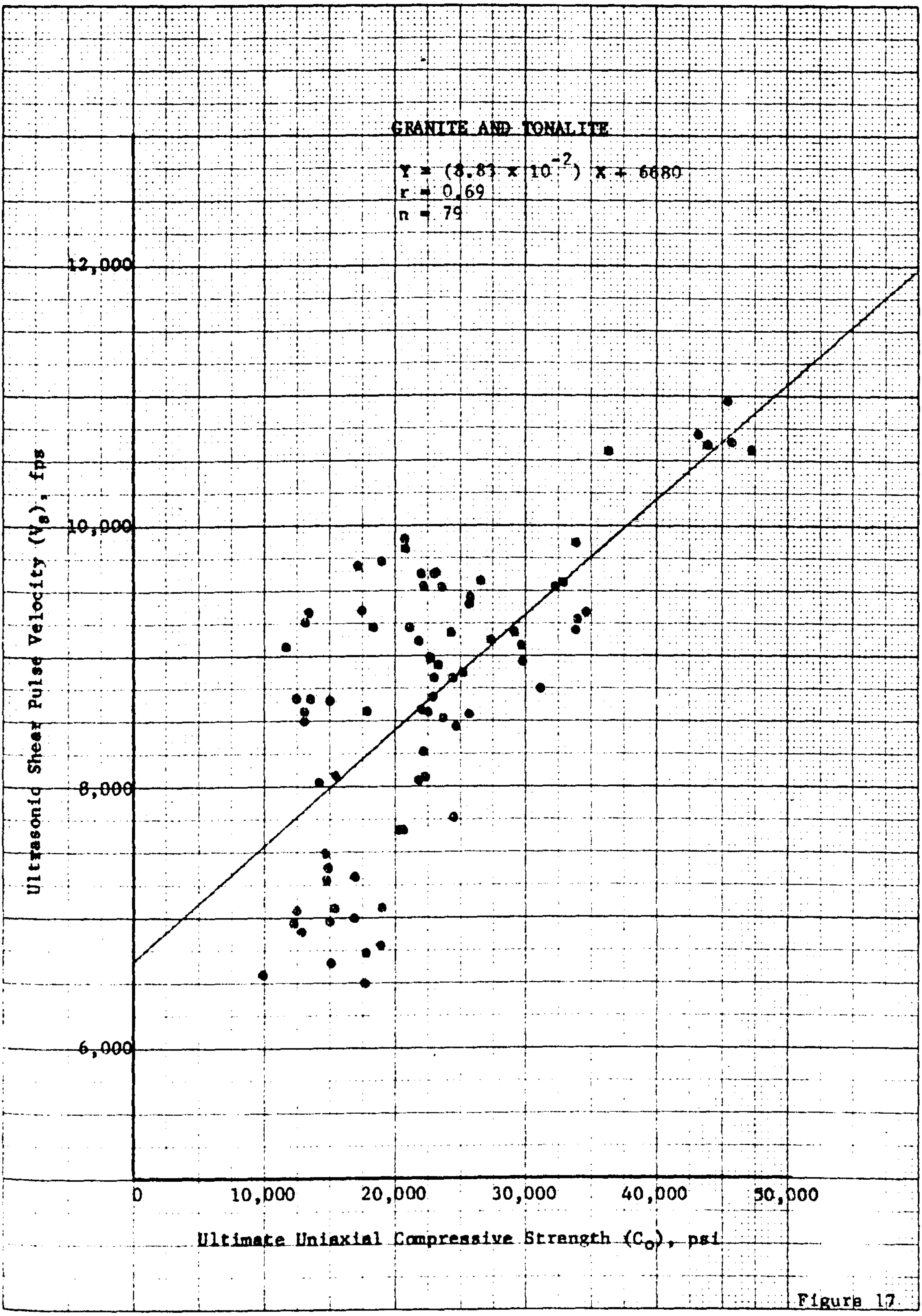

GRANITE AND TONALITE
Y = (8.83 x 10^-2) X + 6680
r = 0.69
n = 79
12,000
10,000
8,000
6,000
Ultrasonic Shear Pulse Velocity (Vs), fps
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (Co), psi

Figure 17

correlation coefficients (Table 3) (r) determined for the Group 2 tonalites were considerably larger than the corresponding critical values (given in Appendix II), while the correlation coefficients determined for the granites alone were only 0.44 and 0.49 for C_0 versus V_p and C_0 versus V_s, respectively, low enough to be of questionable significance.

When the data yielded by the tonalites and granites were combined (for the particular pairs of physical properties) and examined as a single data sample, the result, in both instances, was a rather noticeable increase in scatter over and beyond the scatter typical of either the granite or tonalite data alone. Also, while the resulting correlation coefficients (for the Group 4 data) were slightly higher than those yielded for the granite data alone, they were substantially lower than the values determined for the tonalite data alone. Thus the net effect, in these instances, appears to have been a considerable sacrifice of quality of the better scatter plots and physical property correlations (Group 2 tonalites) resulting from the introduction of data exhibiting trends of a somewhat different character and lesser quality (Group 3 granites).

A comparison of the correlation coefficients (Table 3) determined for the Groups 1 and 2 tonalites and examination of the scatter plots produced from data yielded by these two groups of specimens revealed no significant differences in magnitude of the correlation coefficients or quality of the scatter diagrams for either C_0 versus V_p or C_0 versus V_s. Thus, for these particular correlations, variation in grain size, rather than substantial variation in percentage

TABLE 3

Correlation Coefficients Obtained For Various Pairs of Physical Properties

Physical Properties Correlated	Correlation Coefficients Obtained For: Sierra Nevada Batholith Tonalites (Group 1)	All Tonalites Tested (Group 2)	All Granites Tested (Group 3)	All Granites and Tonalites Tested (Group 4)
C_o vs V_p	0.81	0.83	0.44	0.58
C_o vs V_s	0.86	0.87	0.49	0.69
C_o vs E_{dyn}	0.86	0.87	0.49	0.71
C_o vs G_{dyn}	0.87	0.88	0.50	0.73
C_o vs K_{dyn}	0.81	0.89	0.39	0.58
C_o vs ν_{dyn}	0.49	0.20	0.33	0.24
E_{tan} vs V_p	0.88	0.86	0.89	0.86
E_{tan} vs V_s	0.92	0.92	0.91	0.92
E_{tan} vs E_{dyn}	0.92	0.90	0.90	0.90
E_{tan} vs G_{dyn}	0.93	0.91	0.90	0.91
E_{tan} vs K_{dyn}	0.88	0.79	0.85	0.80
E_{tan} vs ν_{dyn}	0.58	0.11	0.80	0.45

mineral composition and geologic history as allowed within the confines of the specific rock type, appeared to be the primary factor contributing to the degree of scatter in the tonalite data plots.

C_o Versus Ultrasonic Moduli (E_{dyn}, G_{dyn}, and K_{dyn}). Scatter diagrams illustrating the general relationships existing between ultimate uniaxial compressive strength (C_o) and ultrasonic Young's modulus (E_{dyn}), ultrasonic shear modulus (G_{dyn}), and ultrasonic bulk modulus (K_{dyn}) are given in Figures 18 through 29. Correlations and data plots for comparable groups for each of the above three pairs of variables were generally similar, probably a reflection upon the similar origin of the various values of the three different ultrasonic moduli (all were computed from values of ultrasonic shear and compressional pulse velocities and specific gravities determined for the individual specimens).

Of particular interest was the fact that no appreciable changes in magnitudes of coefficients of linear correlation (as opposed to the magnitudes of those values determined for C_o versus V_p and C_o versus V_s) were effected by the use of ultrasonic elastic moduli in correlations with ultimate strength instead of the easier to determine pulse velocities (previously discussed). While correlations of ultimate uniaxial compressive strength (C_o) with ultrasonic shear modulus (G_{dyn}) yielded the highest correlation coefficients of any of the correlations in which ultimate strength was involved as a variable (0.87, 0.88, 0.50, and 0.73 for Groups 1, 2, 3, and 4, respectively), these coefficients were not sufficiently greater than those yielded by correlations of ultimate strength with ultrasonic

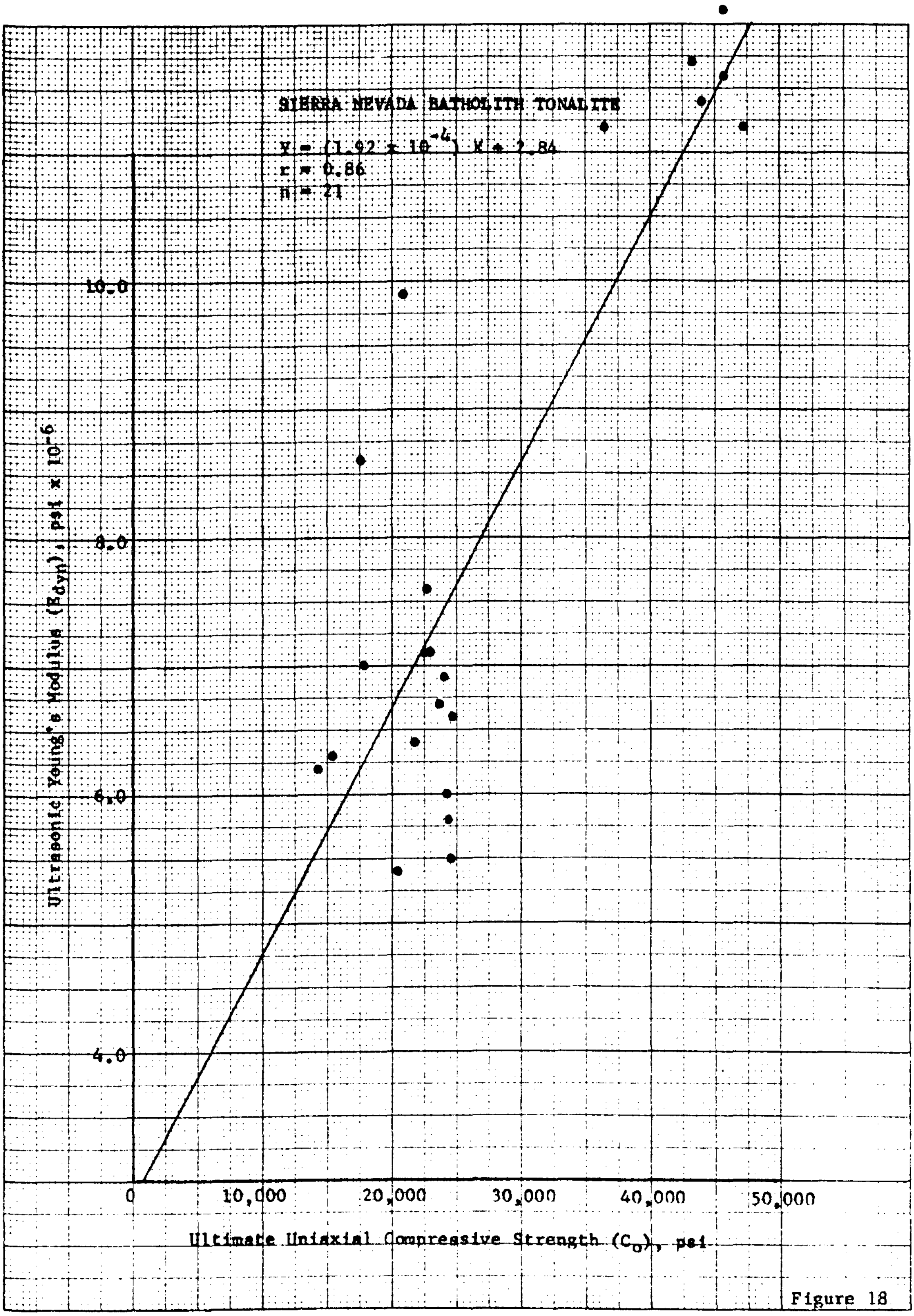

SIERRA NEVADA BATHOLITH TONALITE
Y = (1.92 x 10^-4) X + 2.84
r = 0.86
n = 21
10.0
8.0
6.0
4.0
0
10,000
20,000
30,000
40,000
50,000
Ultrasonic Young's Modulus (E_dyn), psi x 10^-6
Ultimate Uniaxial Compressive Strength (C_o), psi

Figure 18

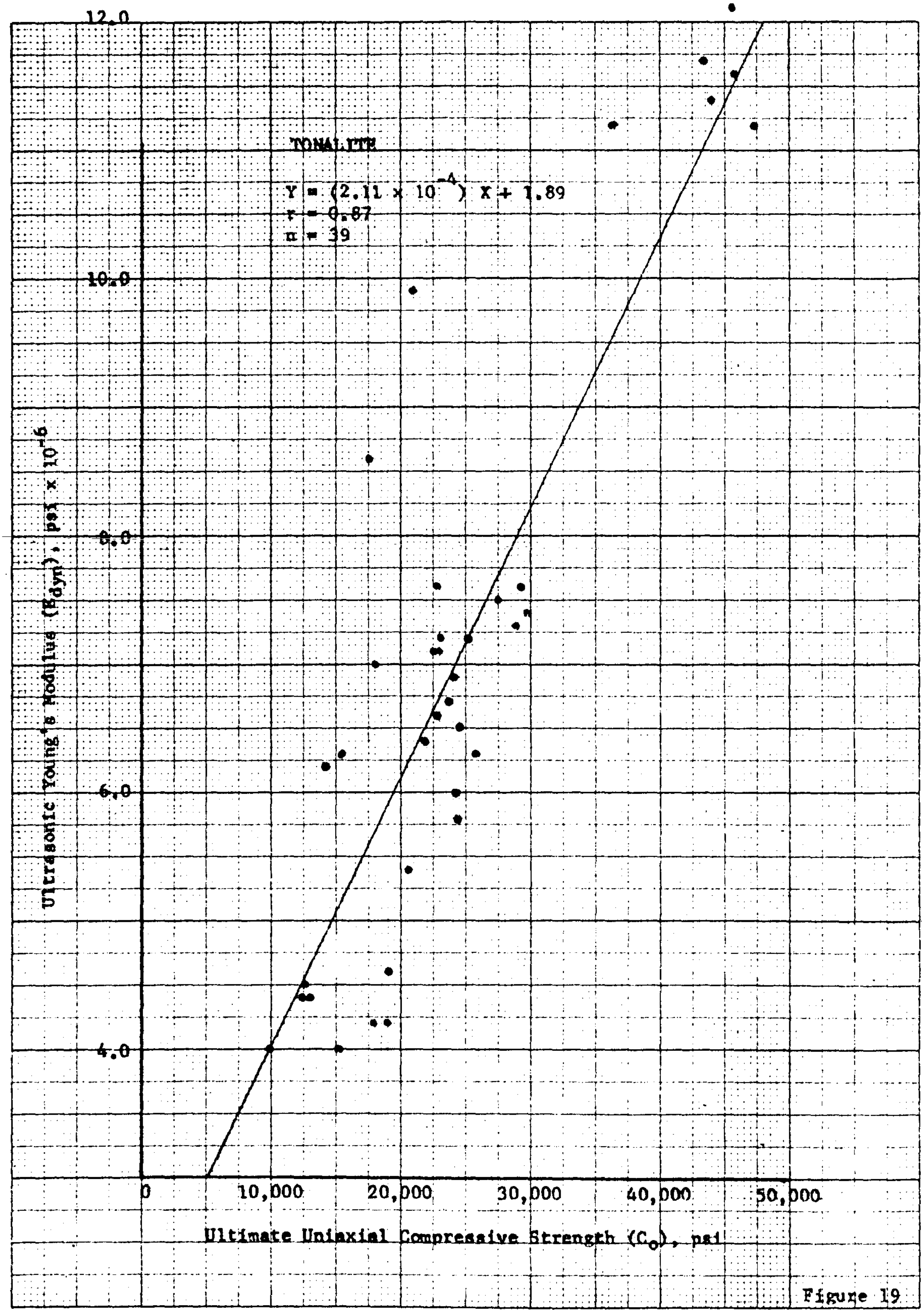

12.0
TONALITE
Y = (2.11 x 10^-4) X + 1.89
r = 0.87
n = 39
10.0
8.0
6.0
4.0
Ultrasonic Young's Modulus (E_dyn), psi x 10^-6
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (C_o), psi

Figure 19

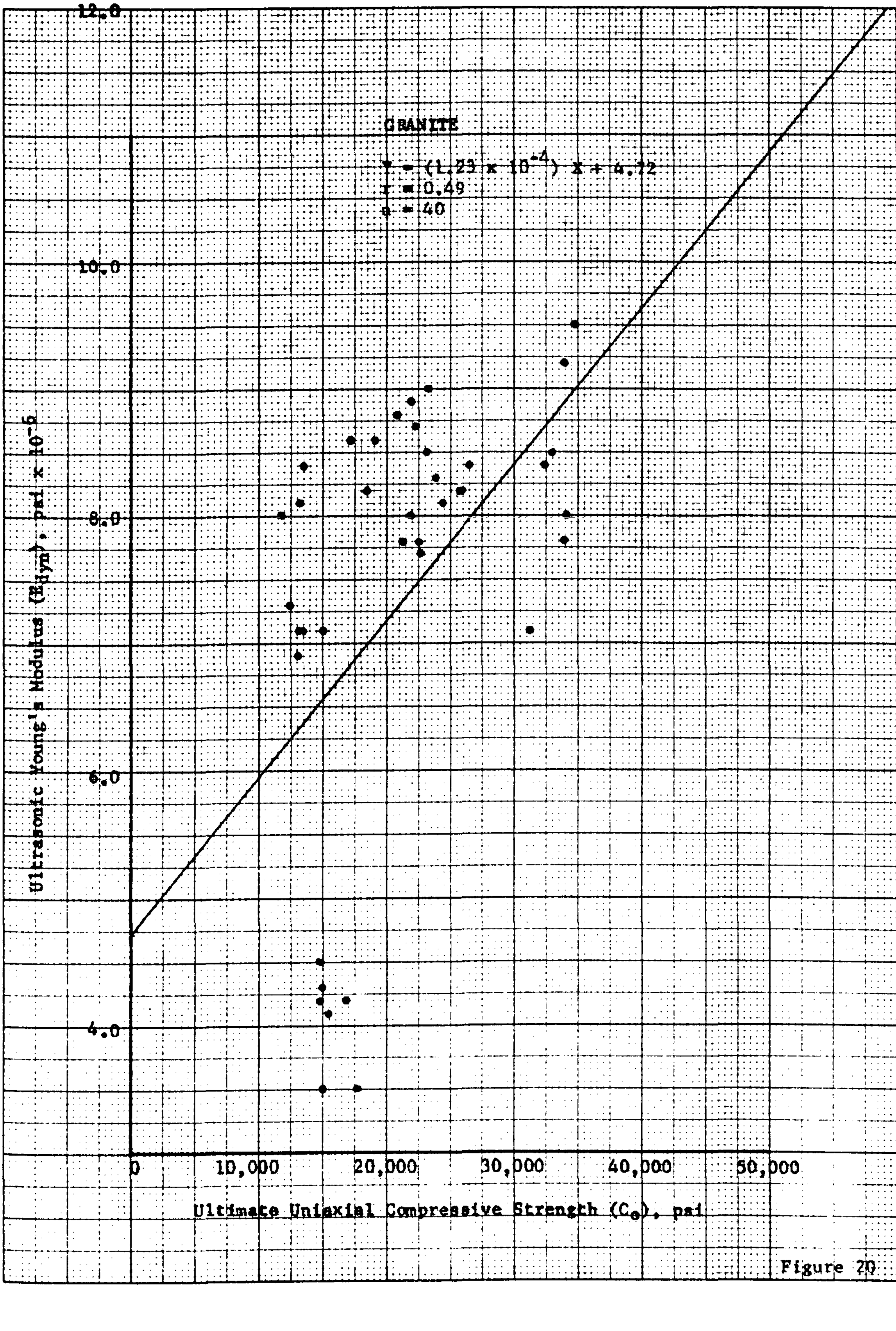
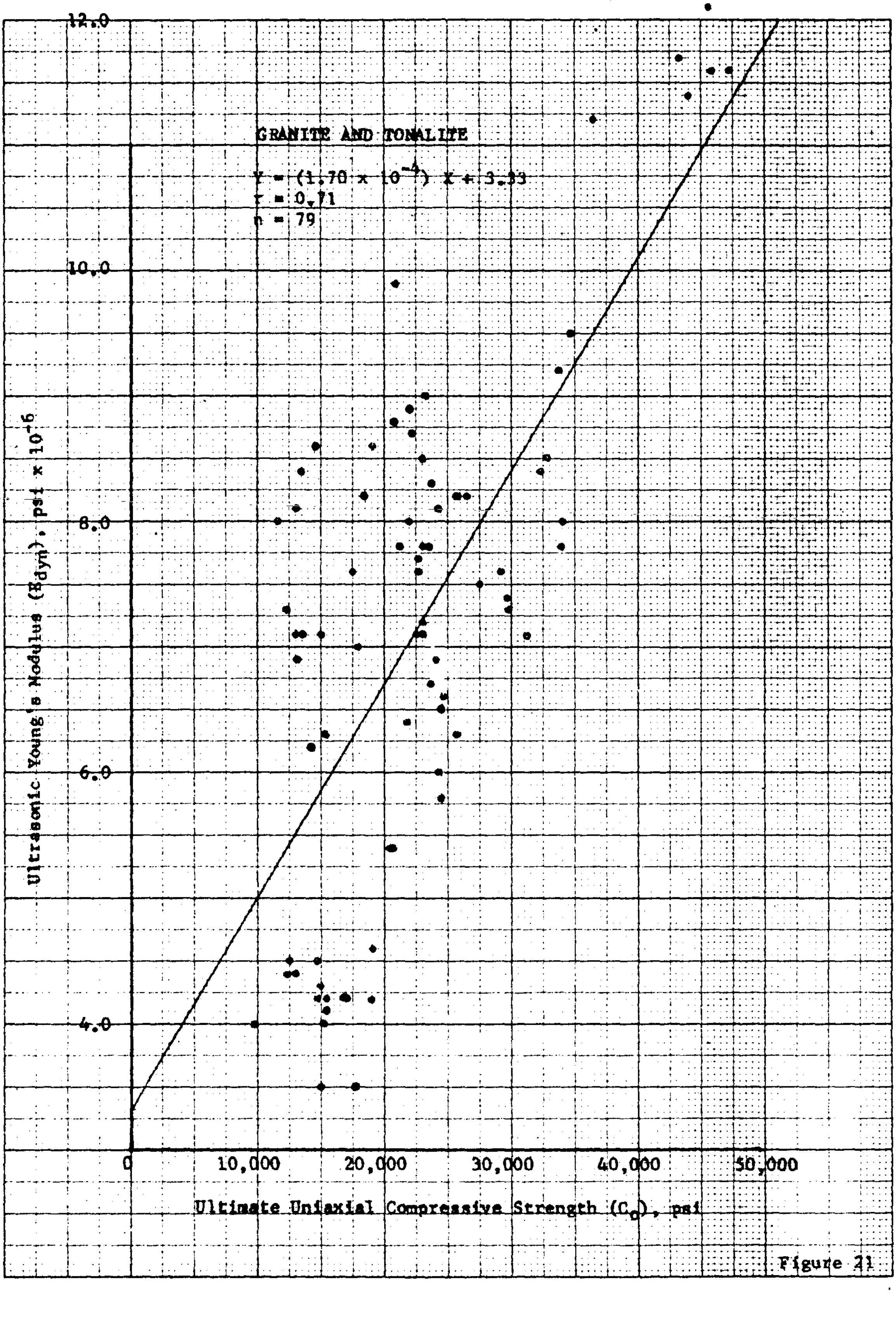

GRANITE
Y = (1.23 x 10^-4) X + 4.72
r = 0.49
n = 40
12.0
10.0
8.0
6.0
4.0
0
10,000
20,000
30,000
40,000
50,000
Ultrasonic Young's Modulus (Edyn), psi x 10^-6
Ultimate Uniaxial Compressive Strength (Co), psi

Figure 20



GRANITE AND TONALITE
Y = (1.70 x 10^-4) X + 3.33
r = 0.71
n = 79
12.0
10.0
8.0
6.0
4.0
0
10,000
20,000
30,000
40,000
50,000
Ultrasonic Young's Modulus (E dyn), psi x 10^-6
Ultimate Uniaxial Compressive Strength (C0), psi

Figure 21

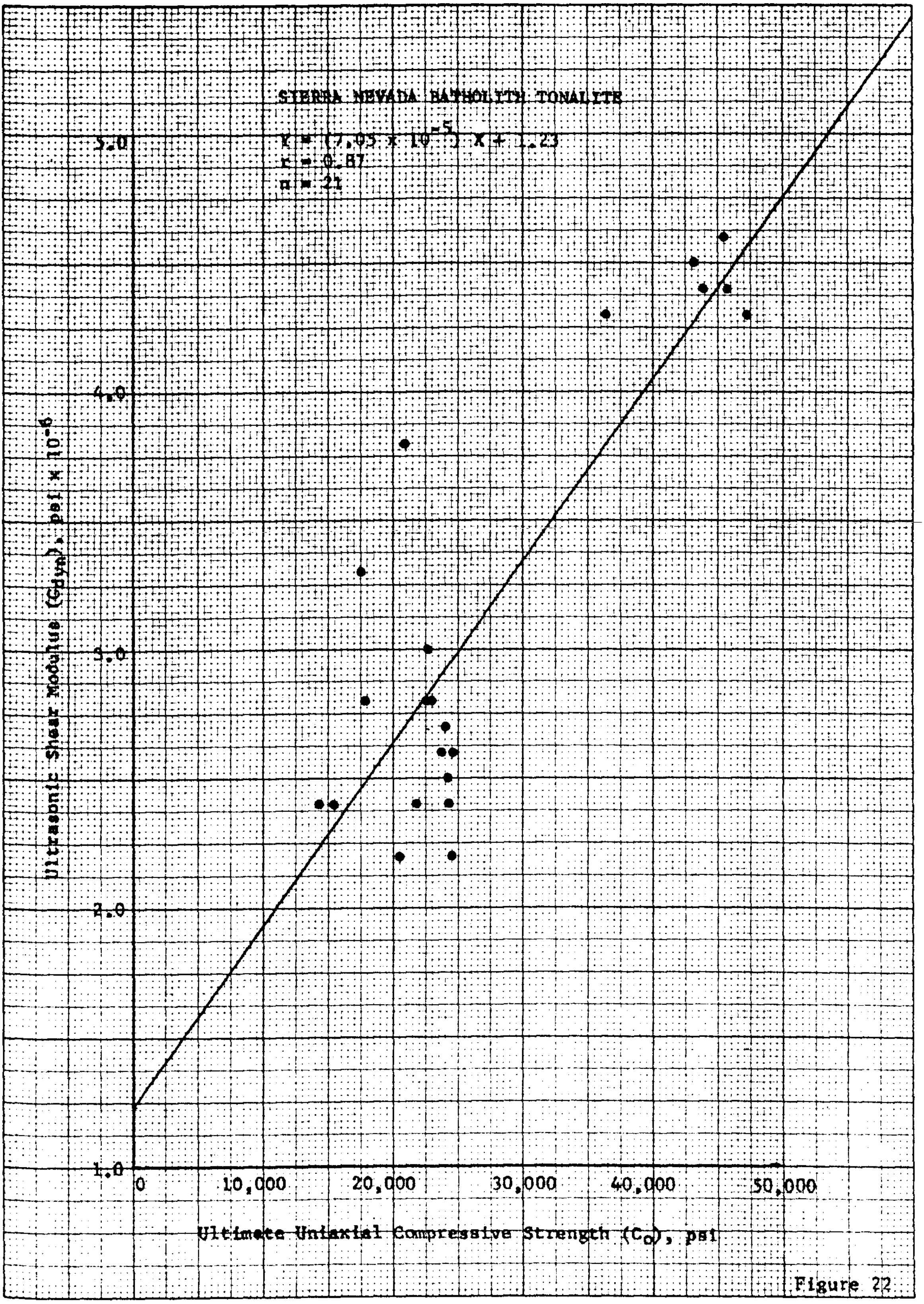

SIERRA NEVADA BATHOLITH TONALITE
Y = (7.05 x 10^-5) X + 1.23
r = 0.87
n = 21
5.0
4.0
3.0
2.0
1.0
Ultrasonic Shear Modulus (Gdyn), psi x 10^-6
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (Co), psi

Figure 22

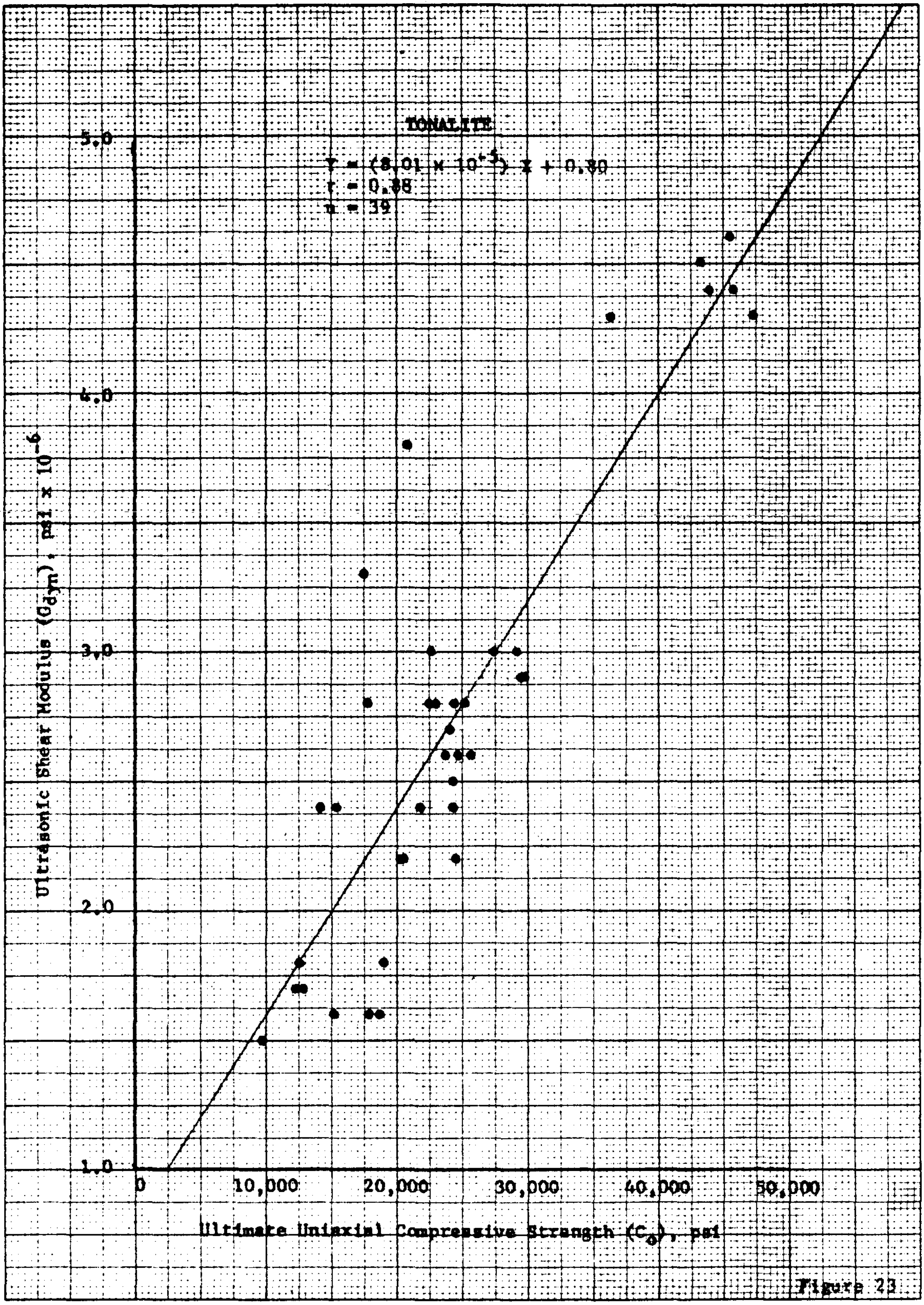
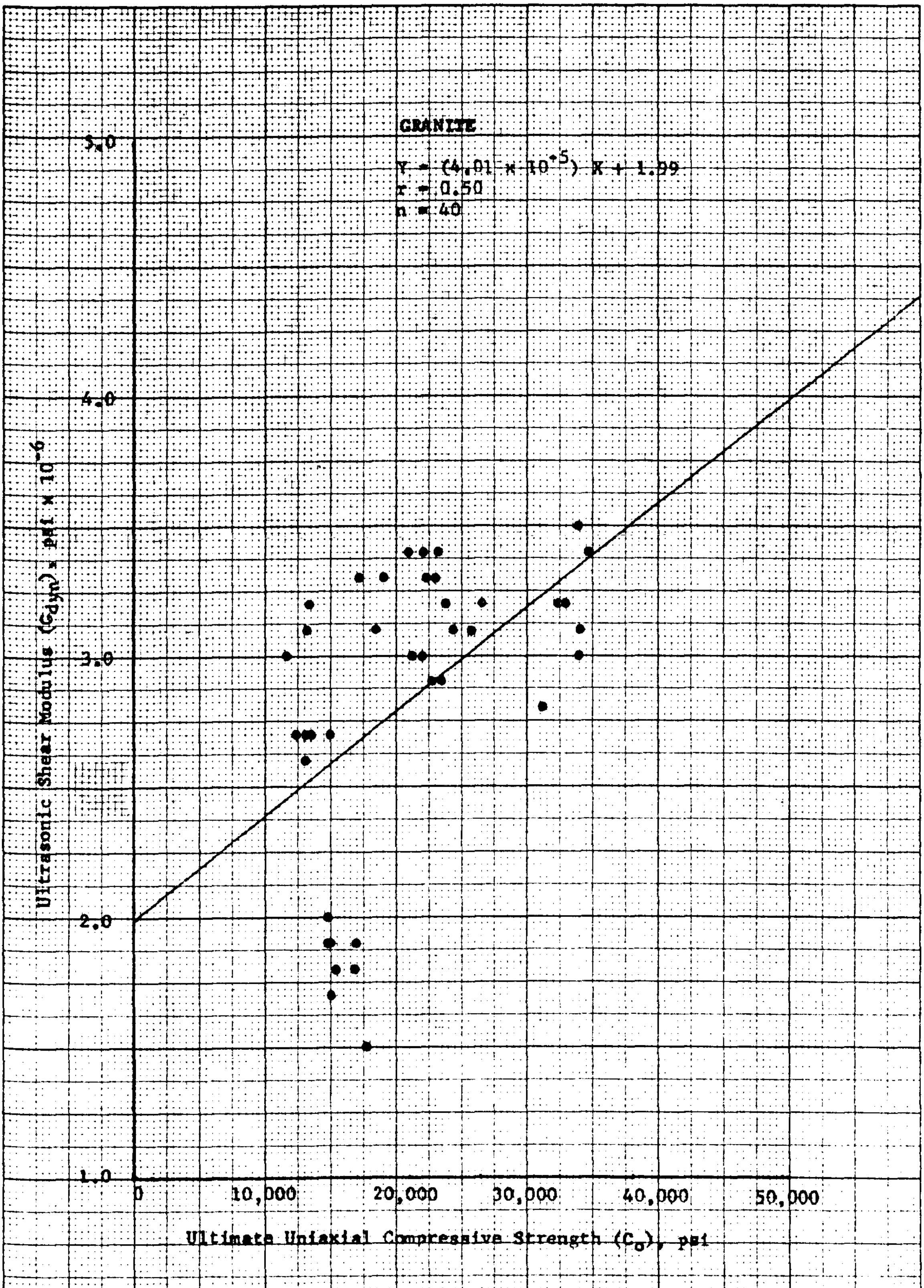

TONALITE
Y = (8.01 x 10^-5) X + 0.80
r = 0.88
n = 39
Ultrasonic Shear Modulus (G_dyn), psi x 10^-6
Ultimate Uniaxial Compressive Strength (C_o), psi
1.0
2.0
3.0
4.0
5.0
0
10,000
20,000
30,000
40,000
50,000

Figure 23


GRANITE
Y = (4.01 x 10^-5) X + 1.99
r = 0.50
n = 40
5.0
4.0
3.0
2.0
1.0
Ultrasonic Shear Modulus (Gdyn), psi x 10^-6
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (Co), psi
Figure 24

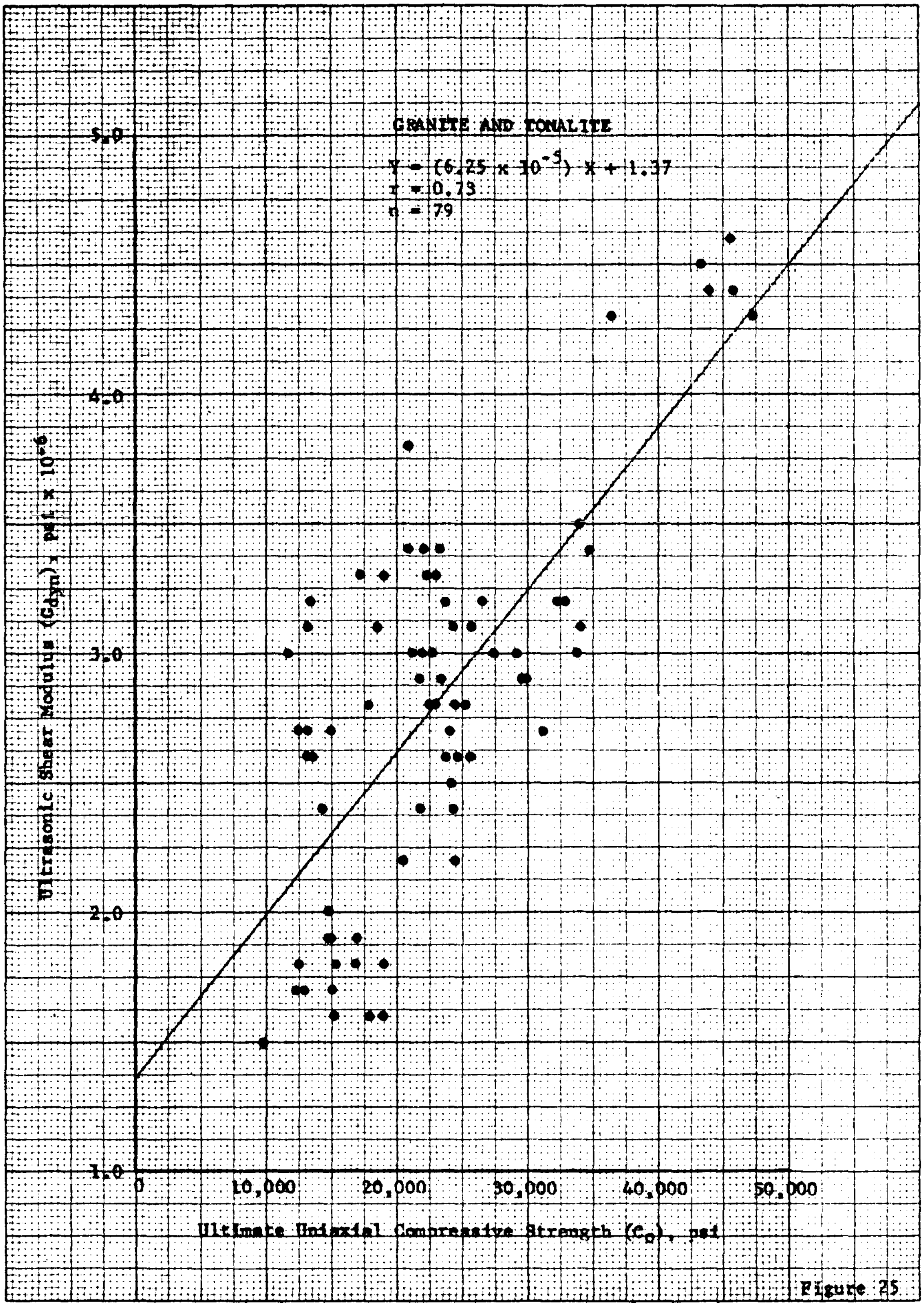
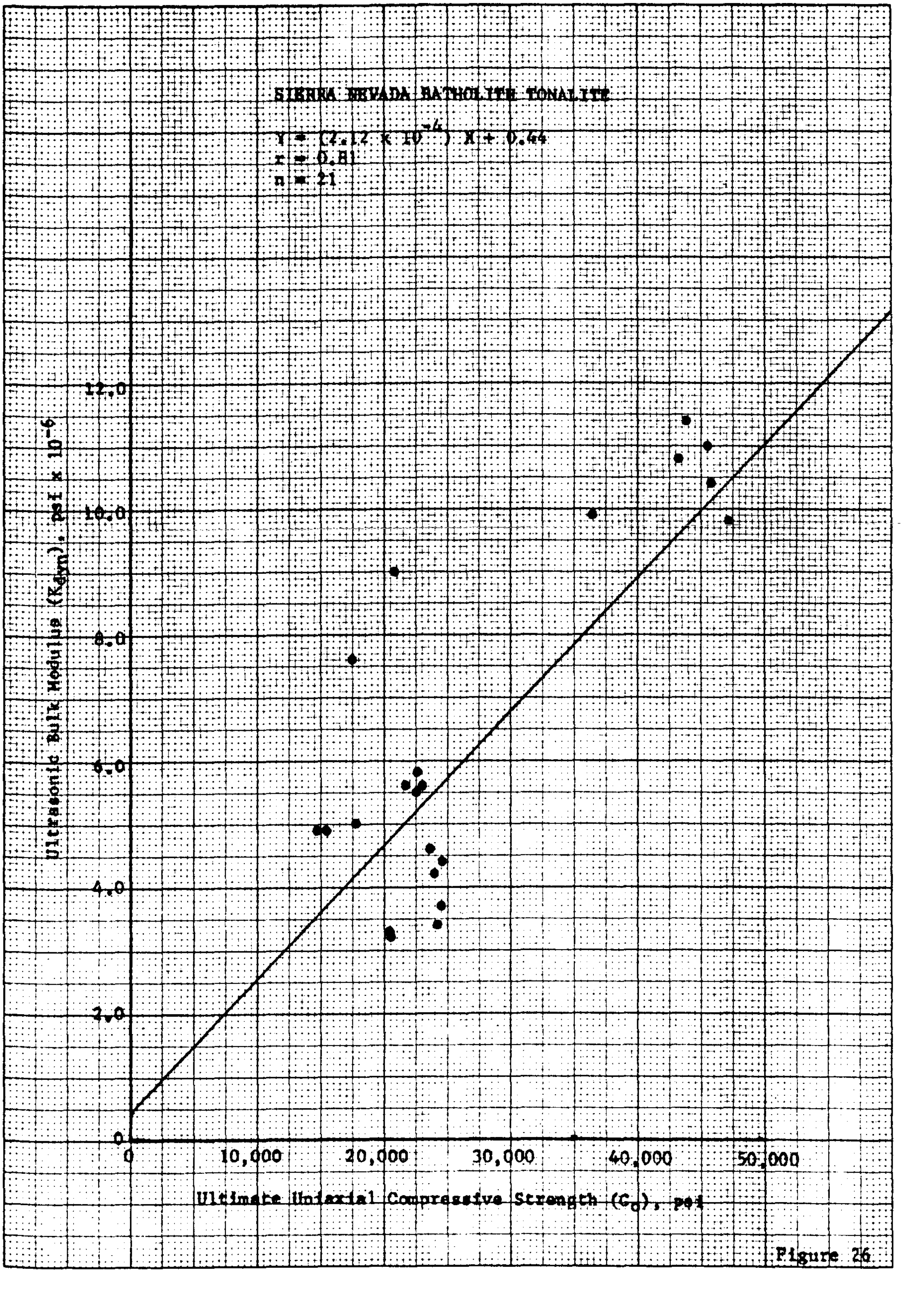
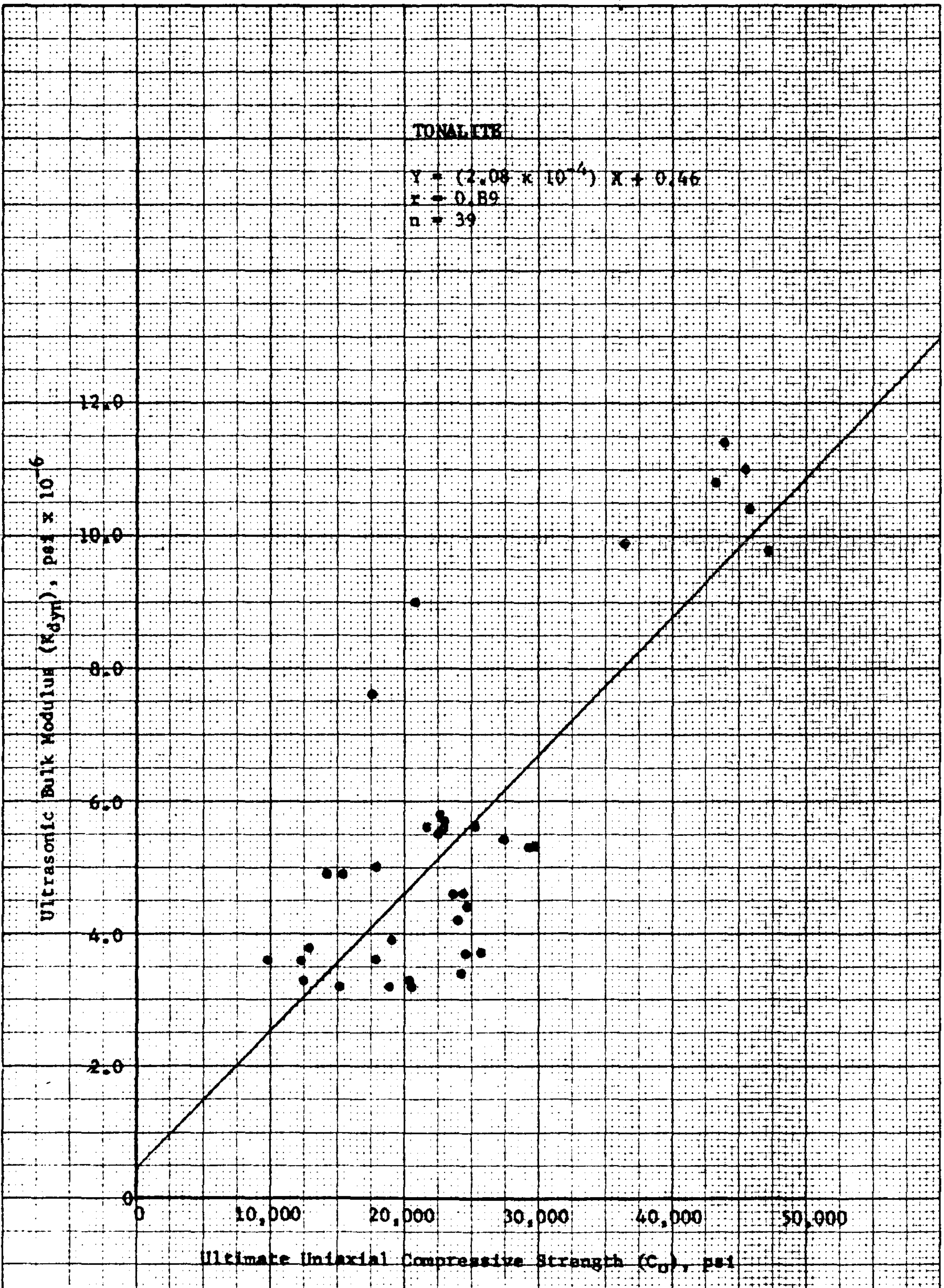

GRANITE AND TONALITE
Y = (6.25 x 10^-5) X + 1.37
r = 0.73
n = 79
5.0
4.0
3.0
2.0
1.0
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (Co), psi
Ultrasonic Shear Modulus (Gdyn), psi x 10^-6

Figure 25



SIERRA NEVADA BATHOLITE TONALITE
Y = (2.12 x 10^-4) X + 0.44
r = 0.81
n = 21
12.0
10.0
8.0
6.0
4.0
2.0
0
Ultrasonic Bulk Modulus (K_dyn), psi x 10^-6
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (C_o), psi

Figure 26



TONALITE
Y = (2.08 x 10^-4) X + 0.46
r = 0.89
n = 39
Ultrasonic Bulk Modulus (K_dyn), psi x 10^-6
12.0
10.0
8.0
6.0
4.0
2.0
0
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (C_o), psi

Figure 27

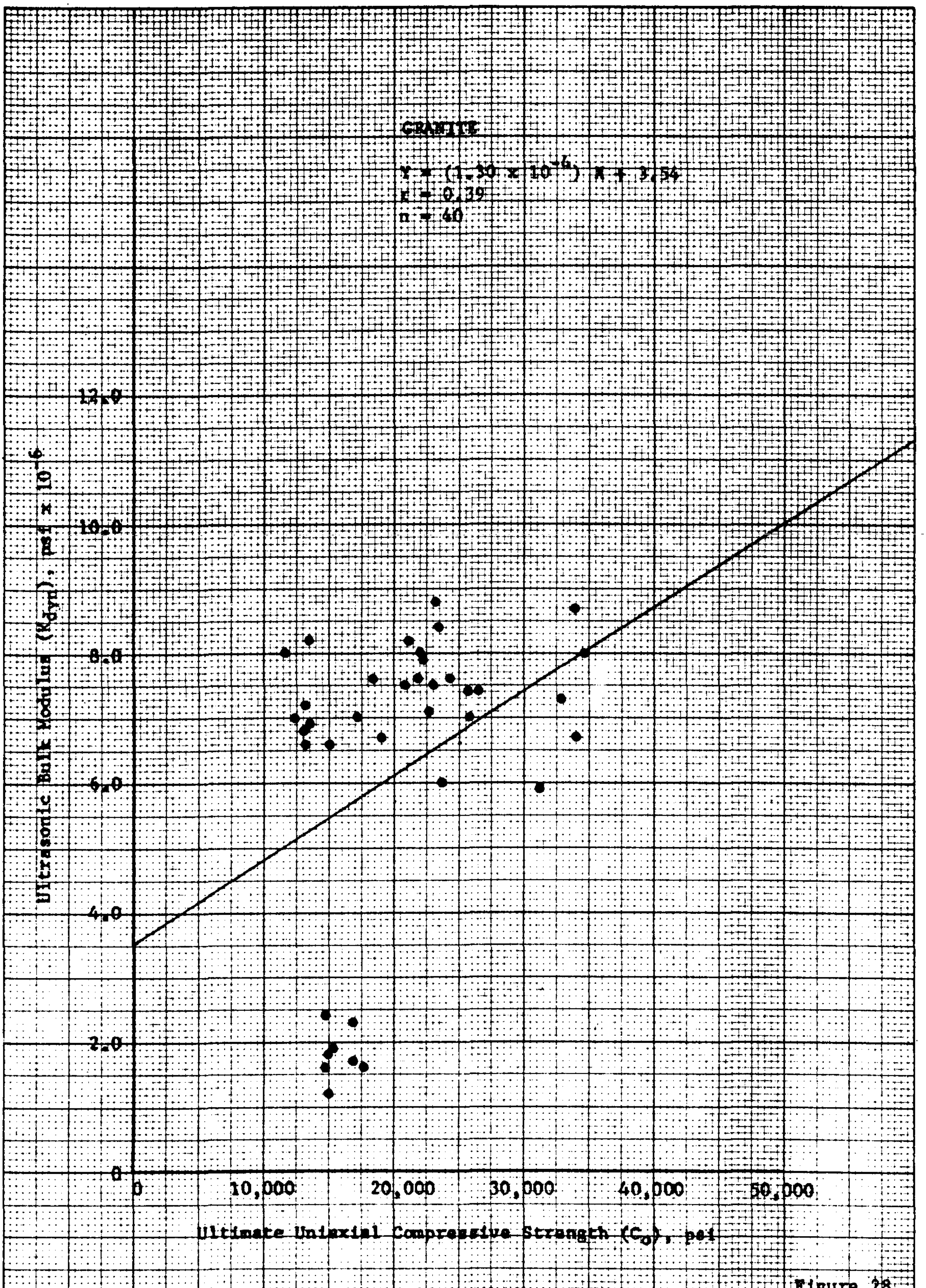

GRANITE
Y = (1.30 x 10^-4) X + 3.54
r = 0.39
n = 40
12.0
10.0
8.0
6.0
4.0
2.0
0
Ultrasonic Bulk Modulus (K_{dyn}), psi x 10^-6
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (C_o), psi

Figure 28

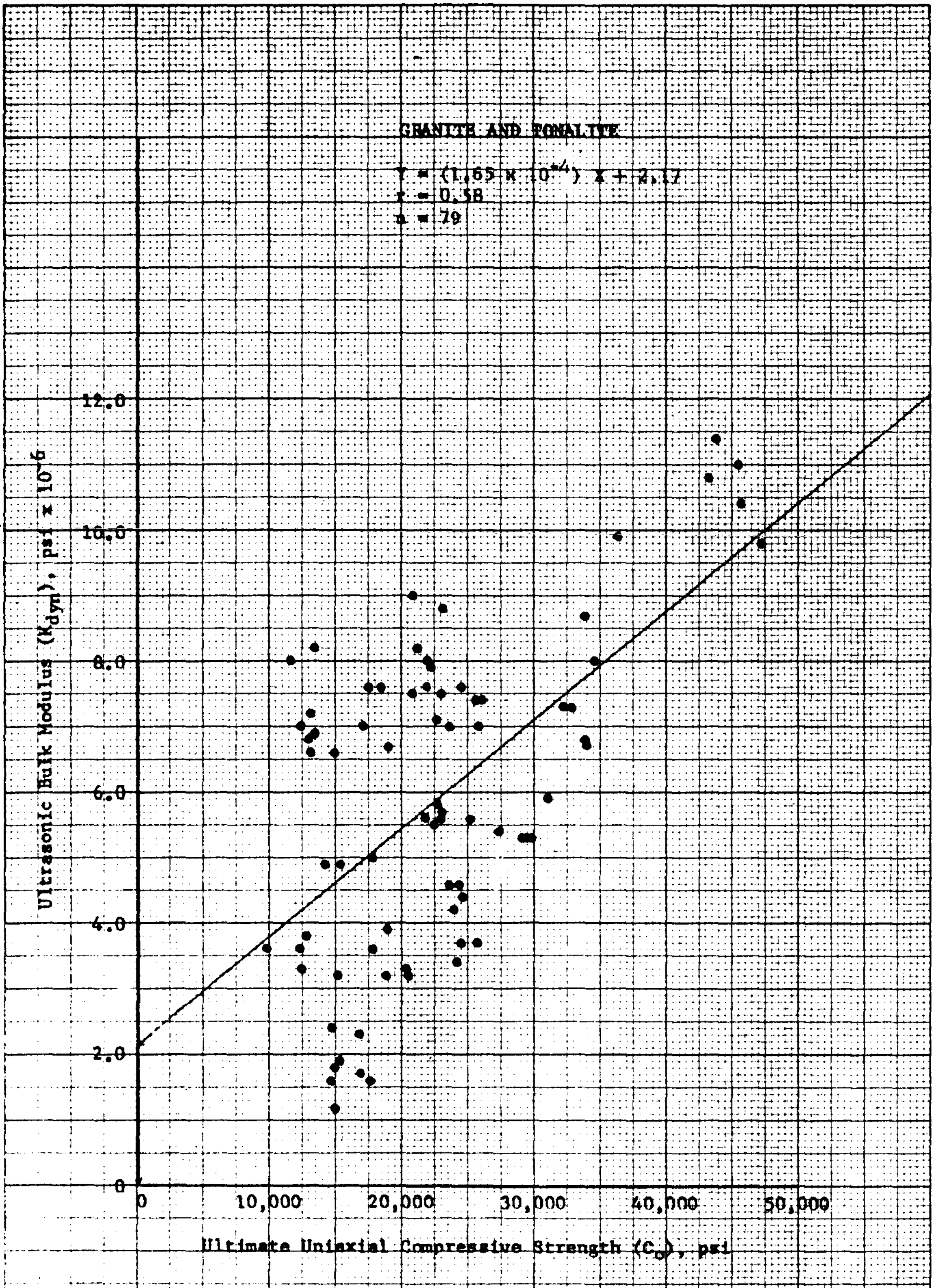

GRANITE AND TONALITE
Y = (1.65 x 10^-4) X + 2.17
r = 0.58
n = 79
Ultrasonic Bulk Modulus (K_{dyn}), psi x 10^{-6}
12.0
10.0
8.0
6.0
4.0
2.0
0
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (C_o), psi

Figure 29

shear pulse velocity (0.86, 0.87, 0.49, and 0.69 for Groups 1, 2, 3, and 4, respectively) to alone justify the additional testing and computation necessary to the determination of ultrasonic shear moduli. This is not to say, however, that determination of ultrasonic elastic moduli would be undesirable.

The same general trends prevalent in the correlations discussed previously (C_0 versus V_p, C_0 versus V_s) were also common to correlations of ultimate strength versus the various ultrasonic moduli. In particular, both groups of tonalite data yielded correlation coefficients of similar magnitudes (Table 3) and scatter diagrams of a similar nature. This apparently reinforces the previous indication that variation in grain size, rather than variation in mineral composition and geologic history as allowed within the confines of a specific rock type, appears to be of primary importance in the determination of the amount of scatter typical of correlations between various properties of this particular rock type.

Furthermore, examination of the correlation coefficients and scatter diagrams determined for the number 2, 3, and 4 data groups indicated, for all three physical property comparisons involving ultimate strength and ultrasonic elastic moduli, that the correlation of data for both rock types as a single statistical sample was undesirable from the point of view that such a procedure resulted in an unnecessary sacrifice in quality of the scatter diagram and degree of correlation typical of the tonalite data alone without yielding an accompanying acceptable increase in quality of the scatter diagram and nature of correlation above those exhibited by the granite data alone.

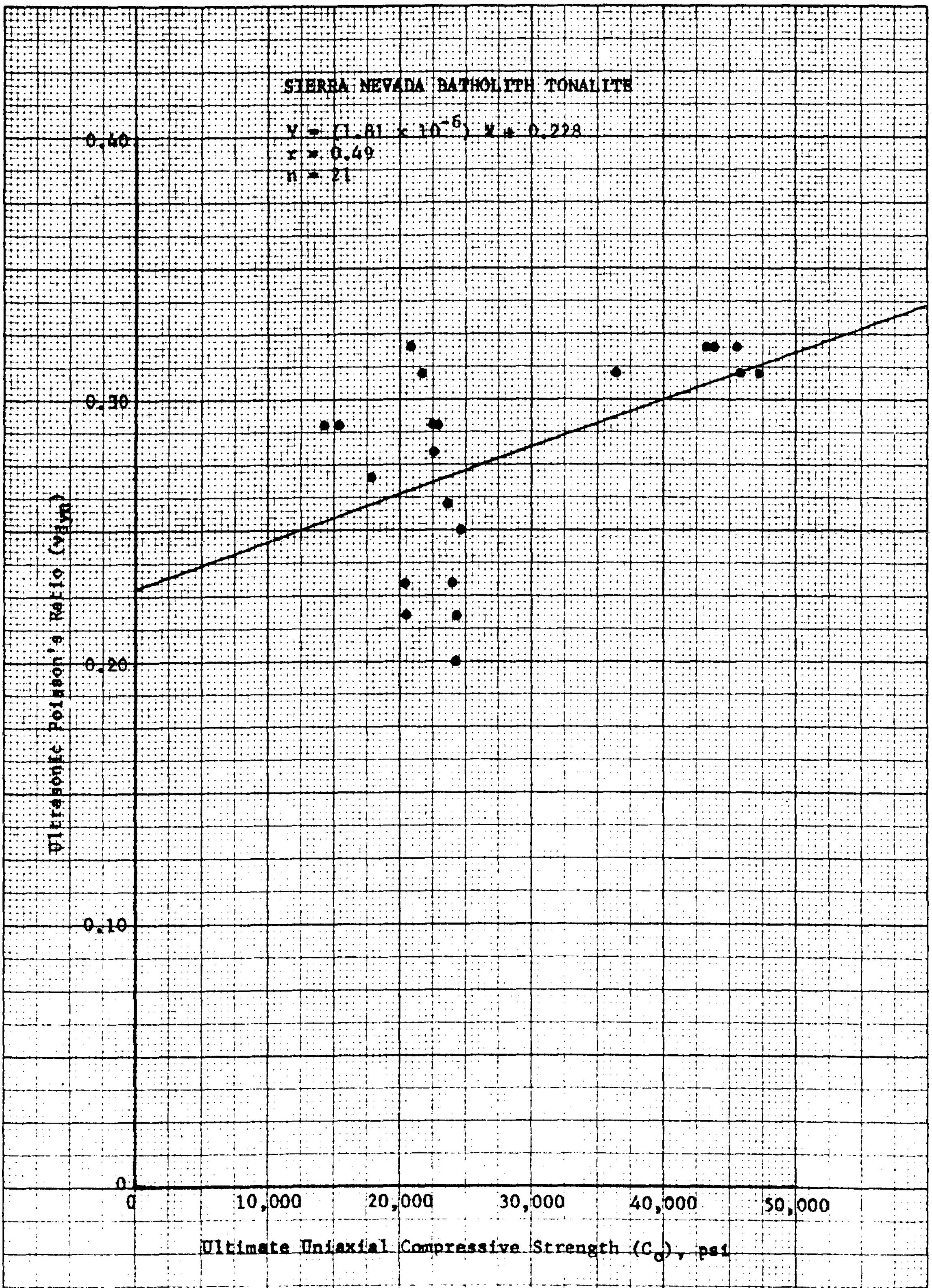
C_o Versus ν_{dyn}. Scatter diagrams illustrating the relationships observed to exist between ultimate uniaxial compressive strength and ultrasonic Poisson's ratio for the four data groups used in this investigation are given in Figures 30 through 33.

Correlation coefficients determined for these data groups (Table 3), were in general, very low, and in all cases but one, were less than the critical values (given in Appendix II), indicating no significant degree of linear association between the two variables. The coefficients were 0.49, 0.20, 0.33, and 0.24 for data groups 1, 2, 3, and 4, respectively.

Figures 30 through 33 further indicate the lack of linear association ~~between the two variables under examination~~, and, in addition, reveal that the higher of the four correlation coefficients owe their larger magnitudes solely to the presence of a few points (eight) of questionable validity (unusually low values of ultrasonic Poisson's ratio) without which these coefficients would be even less significant.

E_{tan} Versus Ultrasonic Pulse Velocities (V_p and V_s). Figures 34 through 37 physically illustrate the relationships existing between values of tangent Young's modulus of elasticity (static) and values of ultrasonic compressional pulse velocity as determined in this study. Figures 38 through 41 depict the relationships existing between values of tangent Young's modulus and values of ultrasonic shear pulse velocity.

Interestingly, the eight correlations (four data groups) determined for these two particular pairs of variables were all quite



SIERRA NEVADA BATHOLITH TONALITE
Y = (1.81 x 10^-6) X + 0.228
r = 0.49
n = 21
0.40
0.30
0.20
0.10
0
0
10,000
20,000
30,000
40,000
50,000
Ultrasonic Poisson's Ratio (νdyn)
Ultimate Uniaxial Compressive Strength (Co), psi

Figure 30

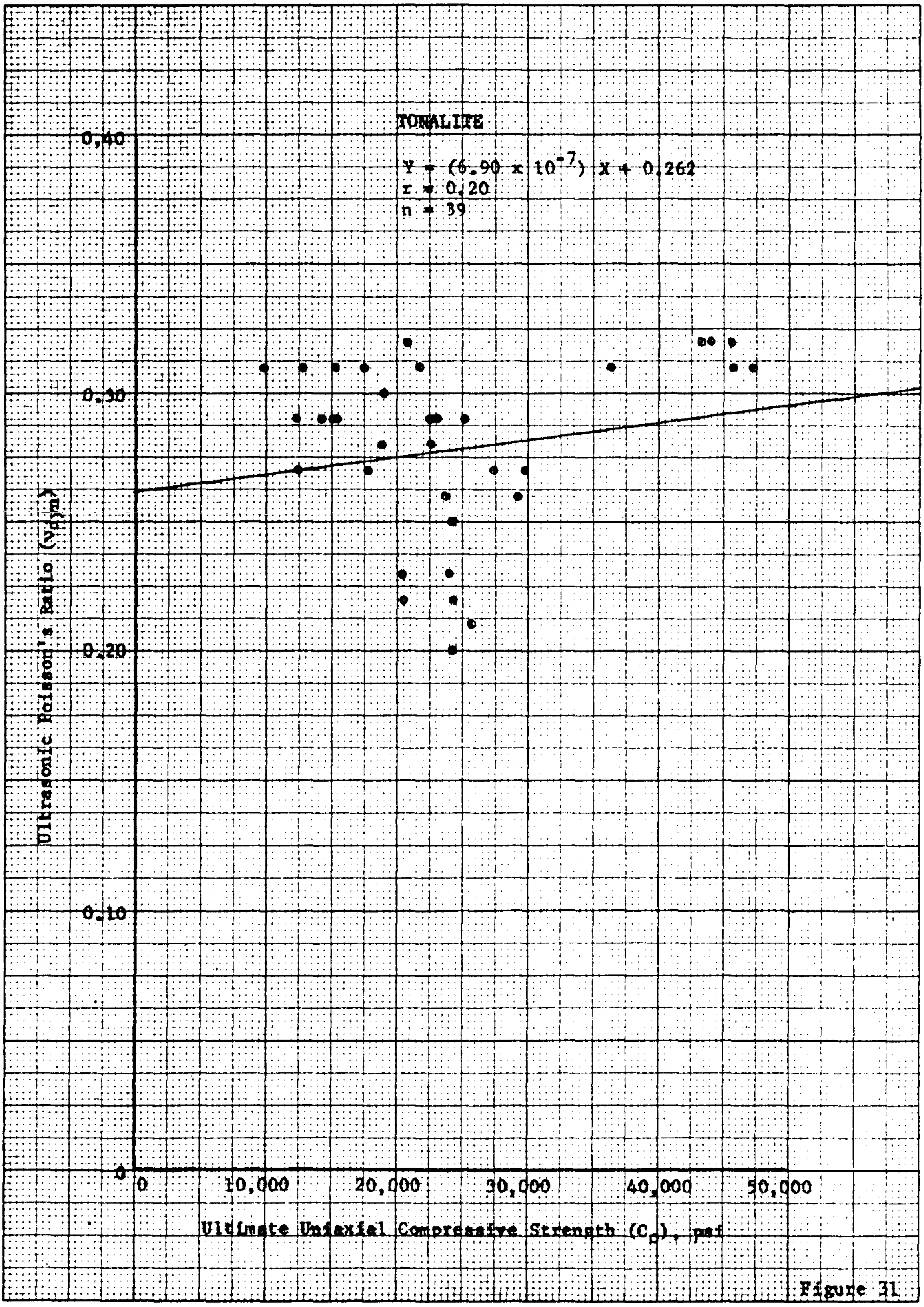

TONALITE
Y = (6.90 x 10^-7) X + 0.262
r = 0.20
n = 39
0.40
0.30
0.20
0.10
0
0
10,000
20,000
30,000
40,000
50,000
Ultrasonic Poisson's Ratio (νdyn)
Ultimate Uniaxial Compressive Strength (Co), psi

Figure 31

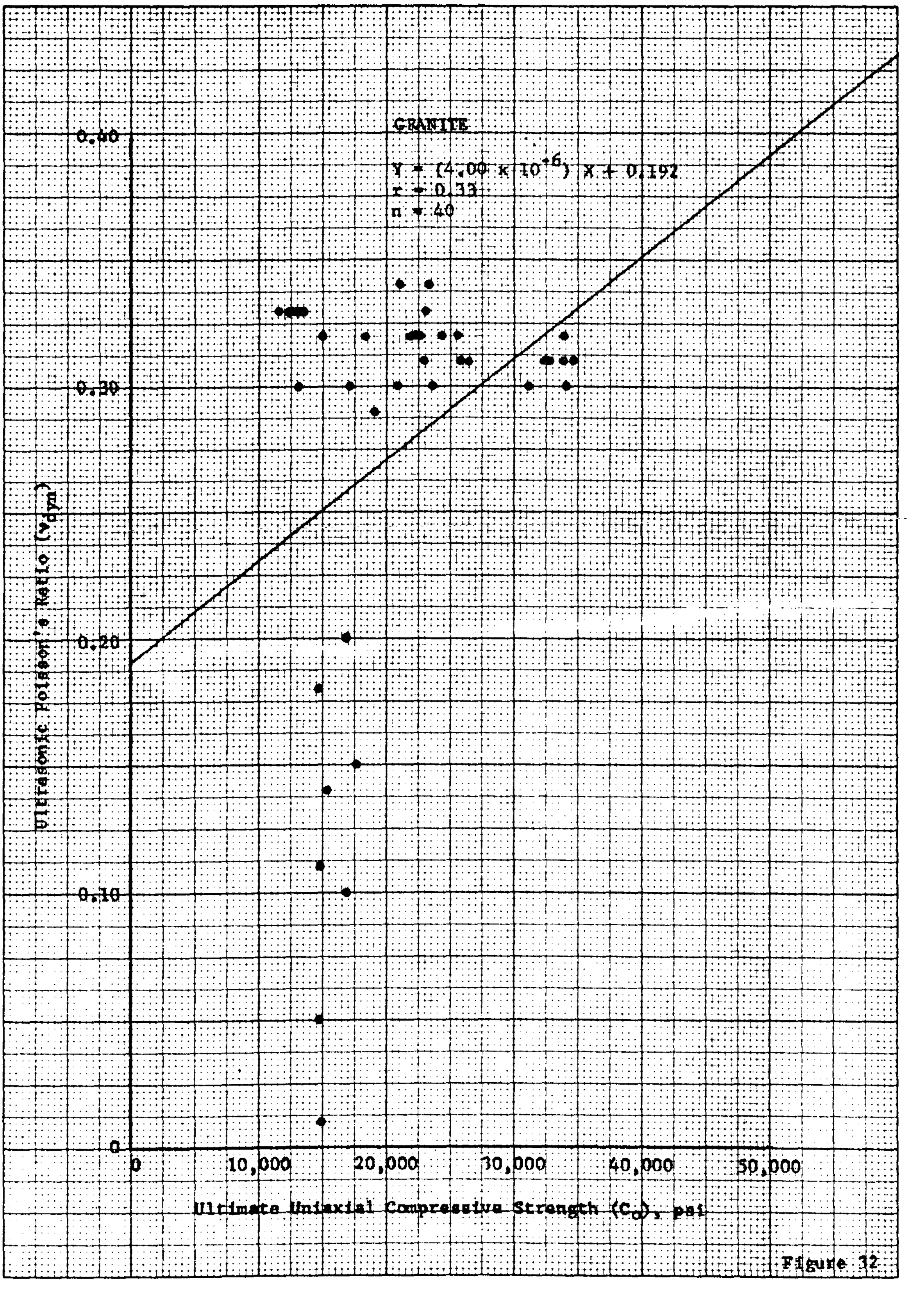

GRANITE
Y = (4.00 x 10^-6) X + 0.192
r = 0.33
n = 40
0.40
0.30
0.20
0.10
0
Ultrasonic Poisson's Ratio (ν_dyn)
0
10,000
20,000
30,000
40,000
50,000
Ultimate Uniaxial Compressive Strength (C_o), psi

Figure 32

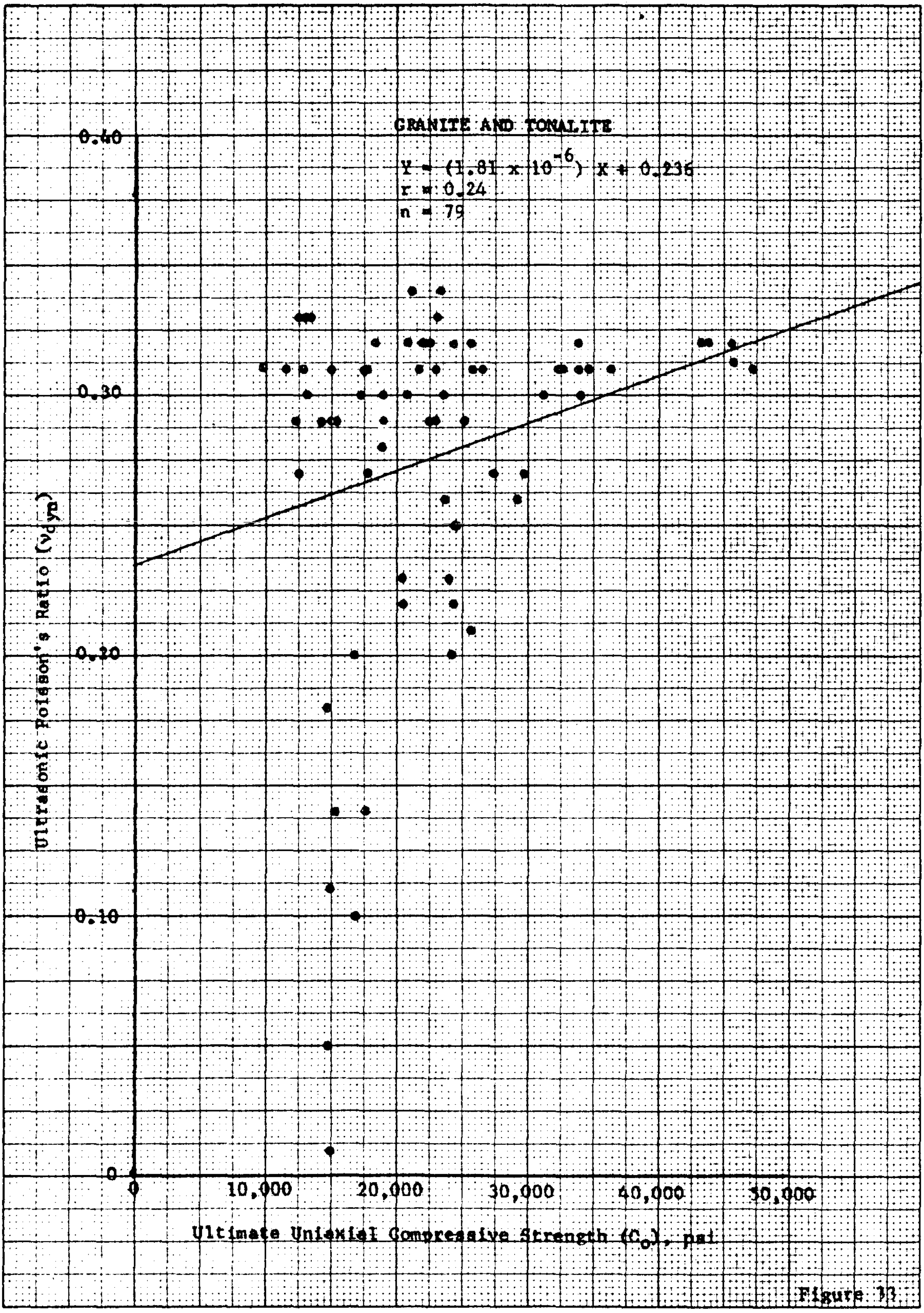

GRANITE AND TONALITE
Y = (1.81 x 10^-6) X + 0.236
r = 0.24
n = 79
0.40
0.30
0.20
0.10
0
10,000
20,000
30,000
40,000
50,000
Ultrasonic Poisson's Ratio (νdym)
Ultimate Uniaxial Compressive Strength (Co), psi

Figure 33

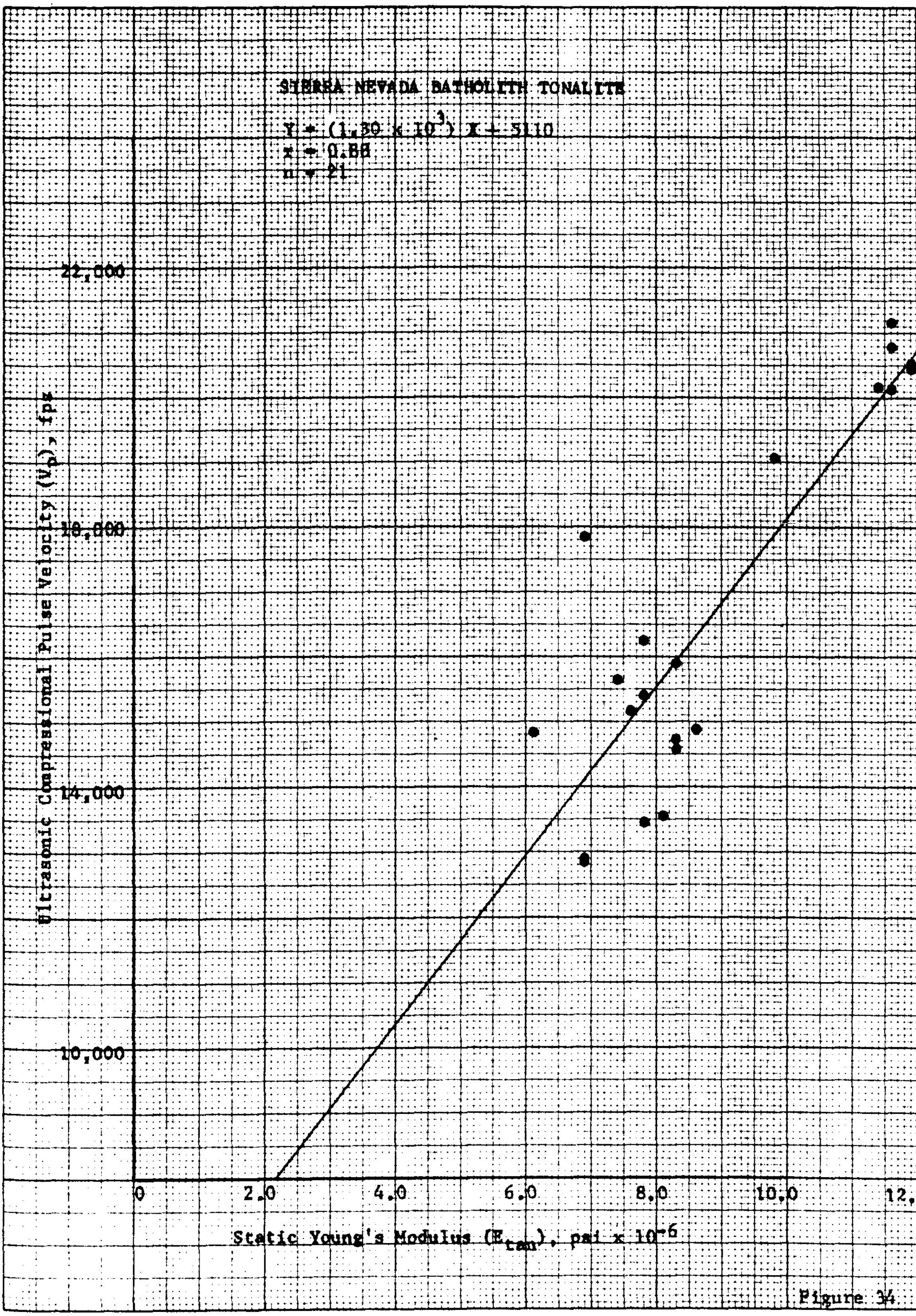

SIERRA NEVADA BATHOLITH TONALITE
Y = (1.30 x 10^3) X + 5110
r = 0.88
n = 21
22,000
18,000
14,000
10,000
Ultrasonic Compressional Pulse Velocity (V_p), fps
0
2.0
4.0
6.0
8.0
10.0
12.0
Static Young's Modulus (E_tan), psi x 10^-6

Figure 34

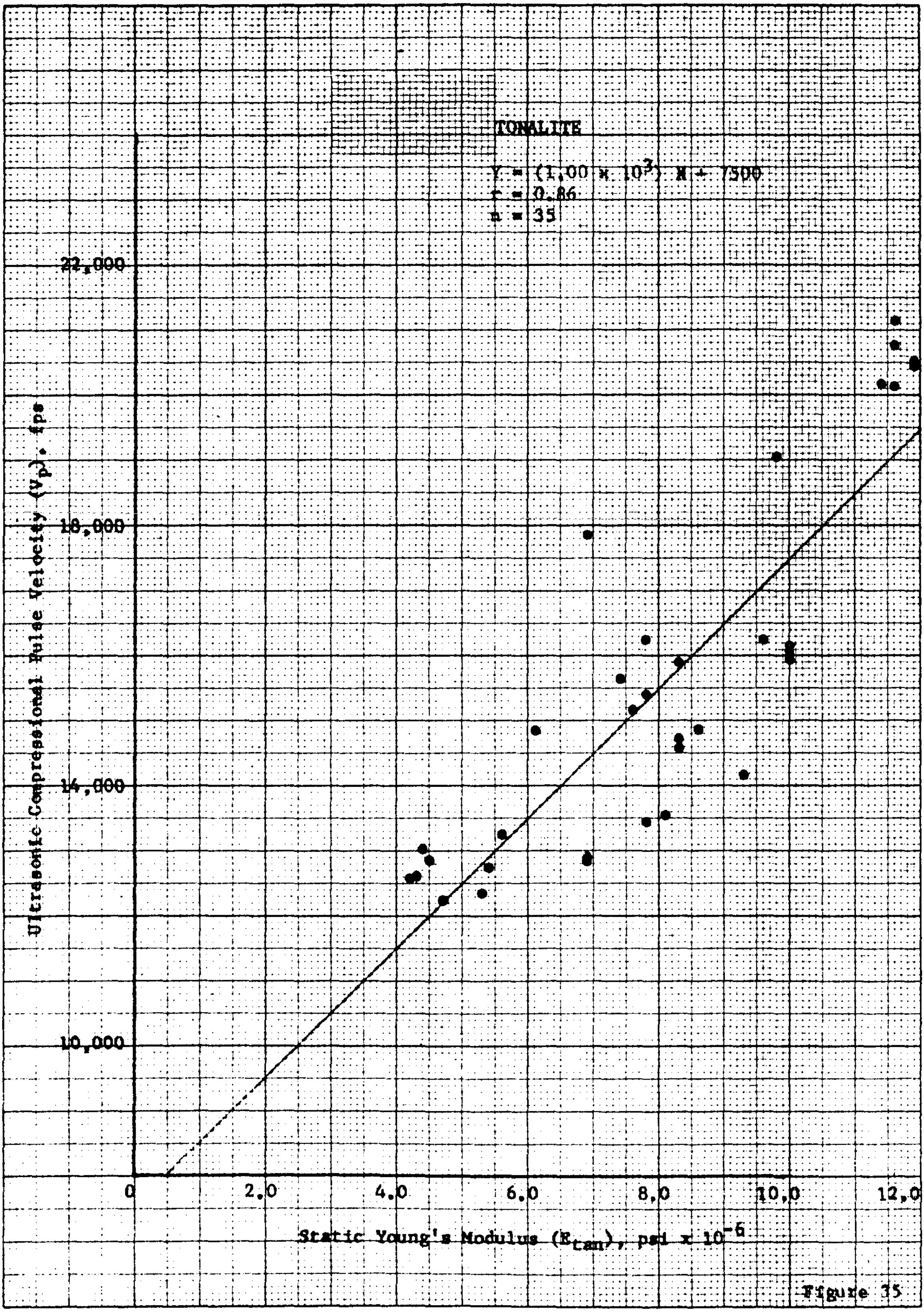
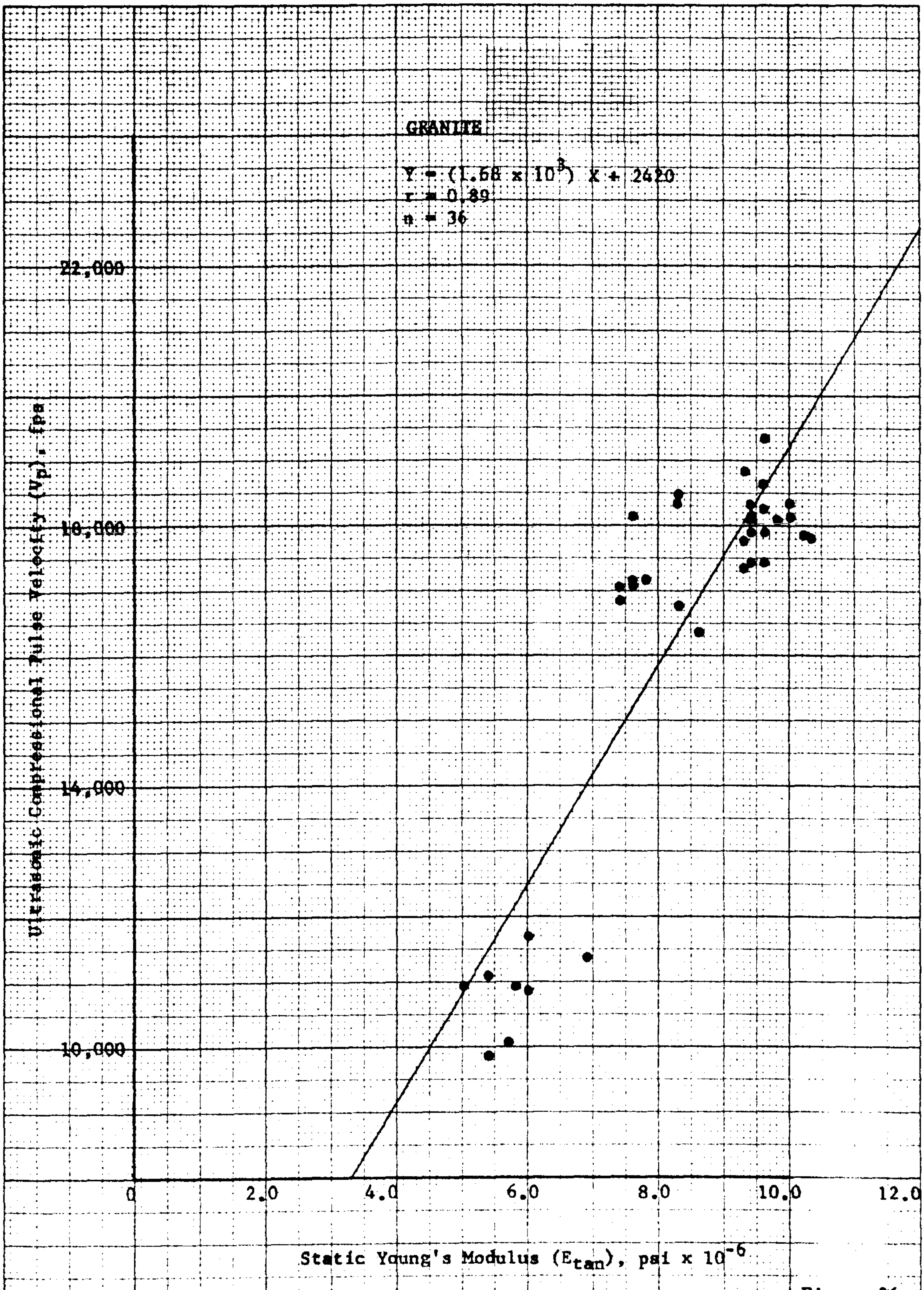
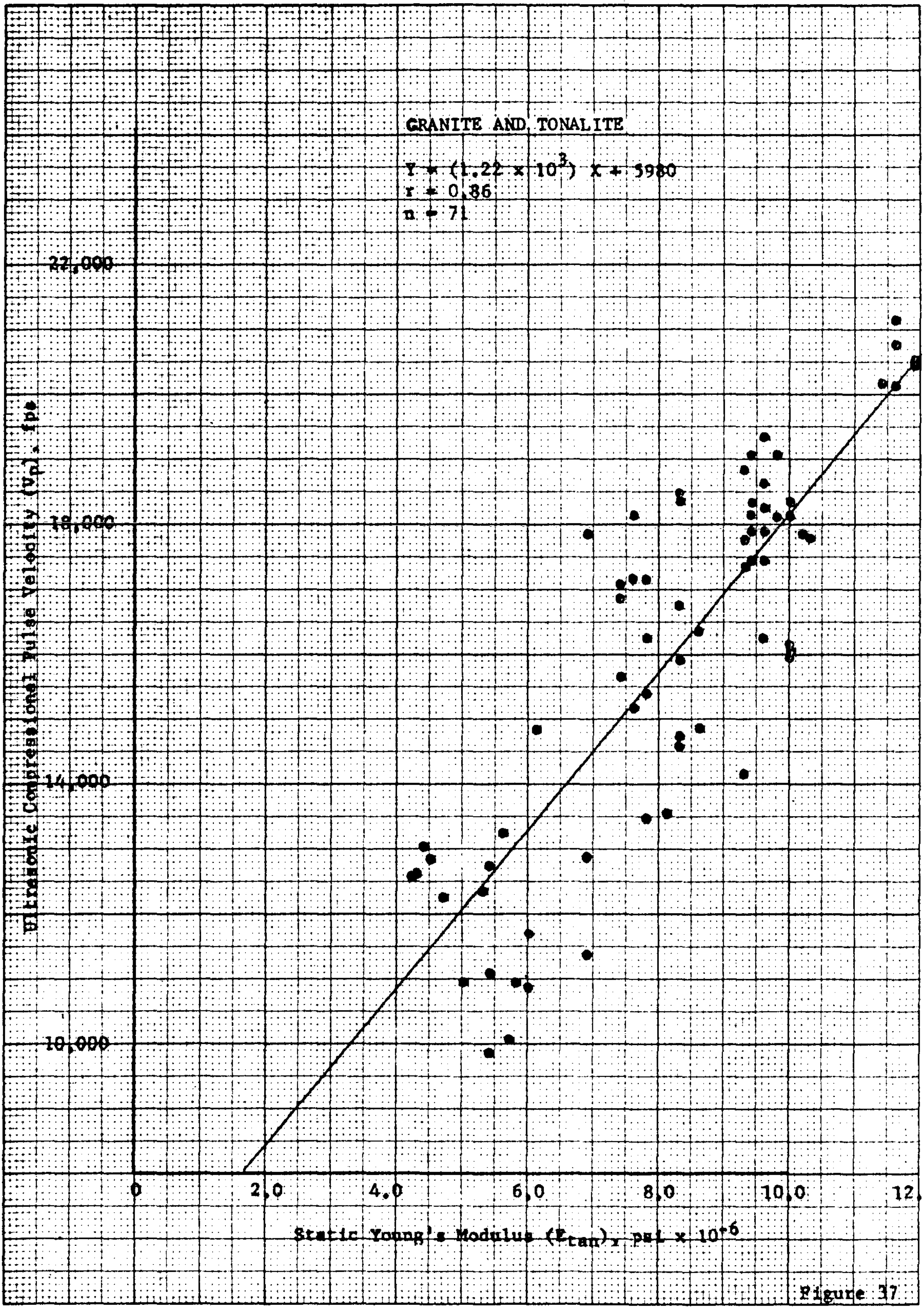

TONALITE
Y = (1.00 x 10^3) X + 7500
r = 0.86
n = 35
22,000
18,000
14,000
10,000
0
2.0
4.0
6.0
8.0
10.0
12.0
Ultrasonic Compressional Pulse Velocity (Vp), fps
Static Young's Modulus (Etan), psi x 10^-6

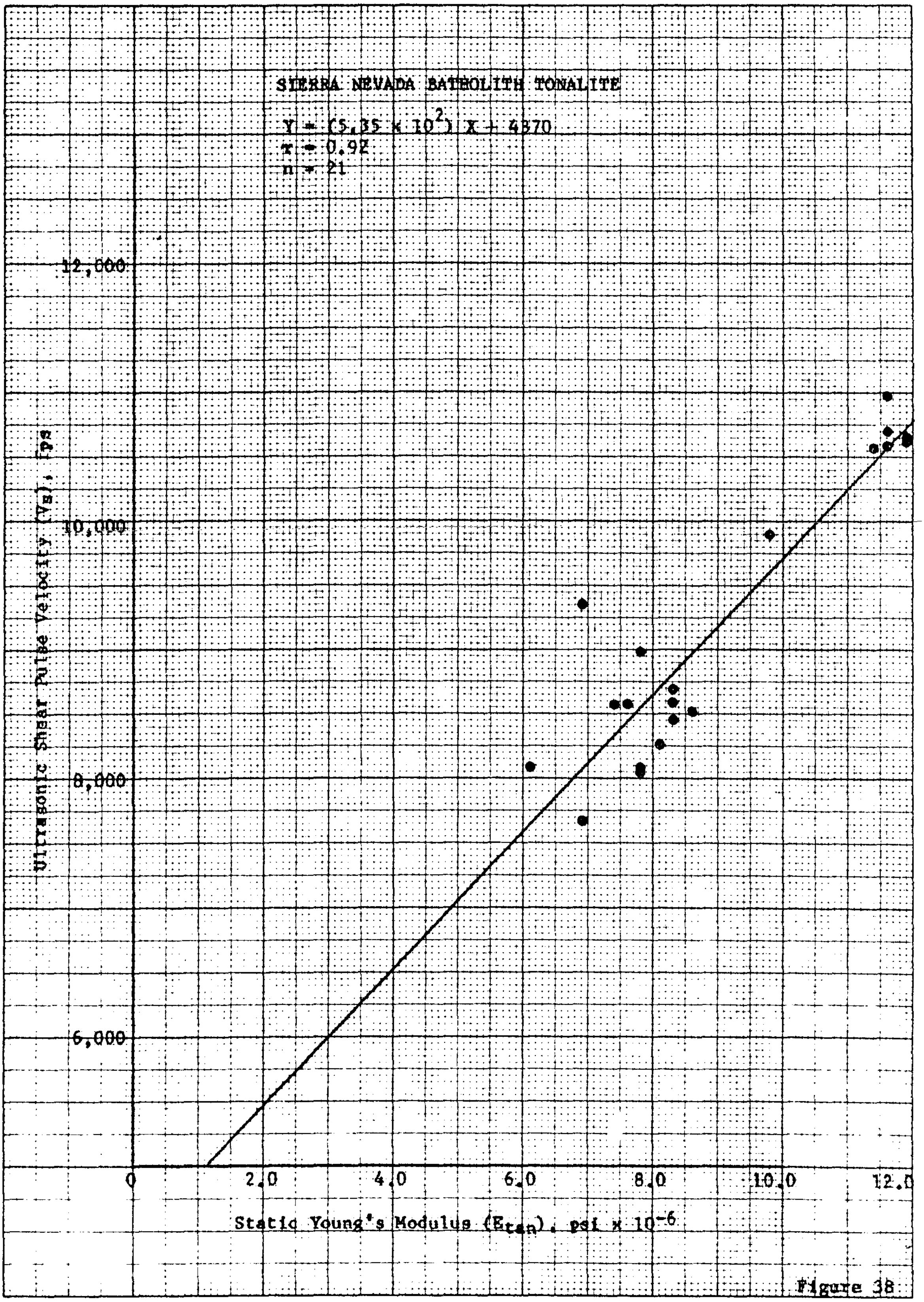
Figure 35

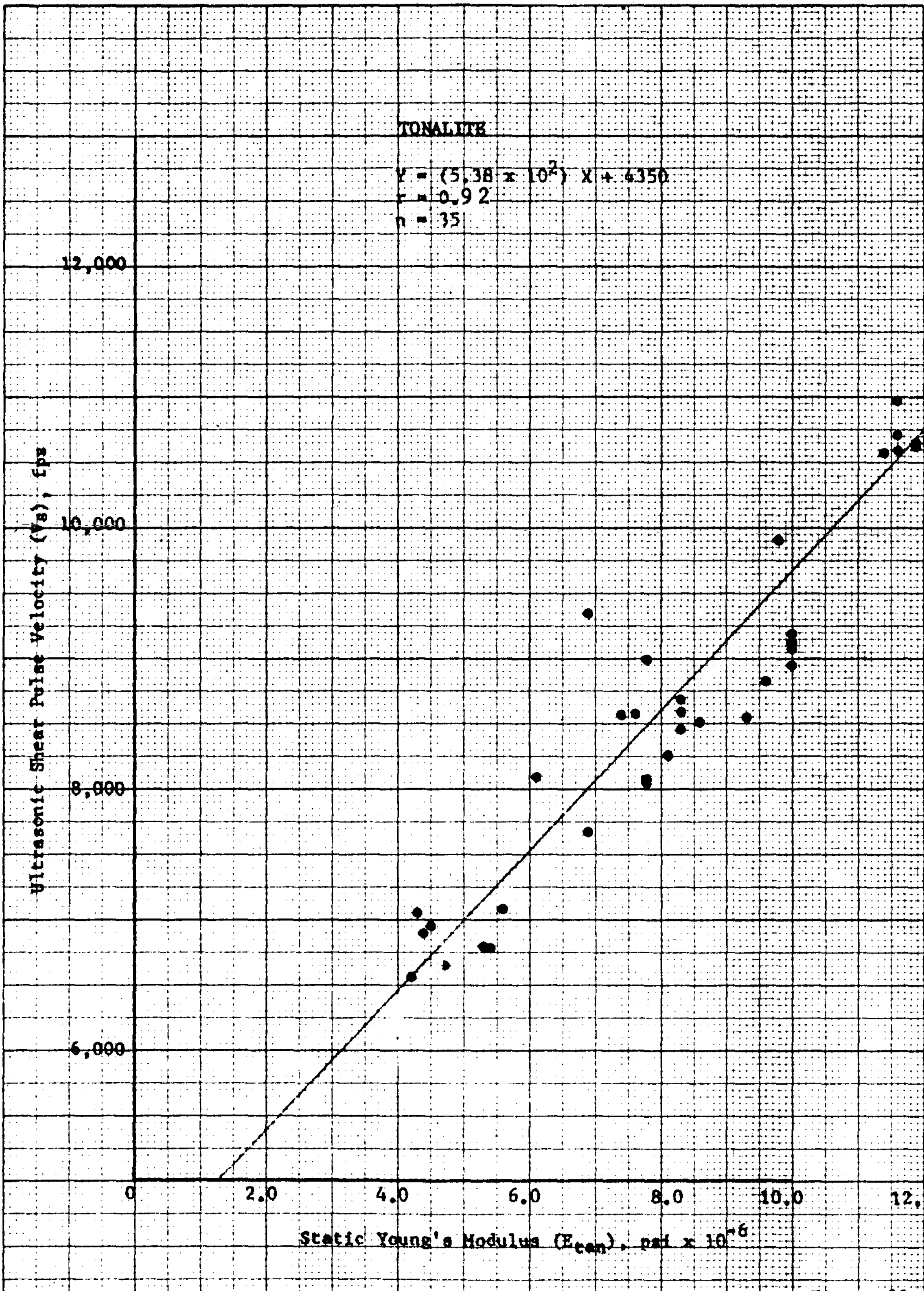

GRANITE
Y = (1.68 x 10^3) X + 2420
r = 0.89
n = 36
22,000
18,000
14,000
10,000
Ultrasonic Compressional Pulse Velocity (Vp), fps
0
2.0
4.0
6.0
8.0
10.0
12.0
Static Young's Modulus (Etan), psi x 10^-6
Figure 36



GRANITE AND TONALITE
Y = (1.22 x 10³) X + 5980
r = 0.86
n = 71
22,000
18,000
14,000
10,000
Ultrasonic Compressional Pulse Velocity (Vp), fps
0
2.0
4.0
6.0
8.0
10.0
12.0
Static Young's Modulus (Etan), psi x 10⁻⁶

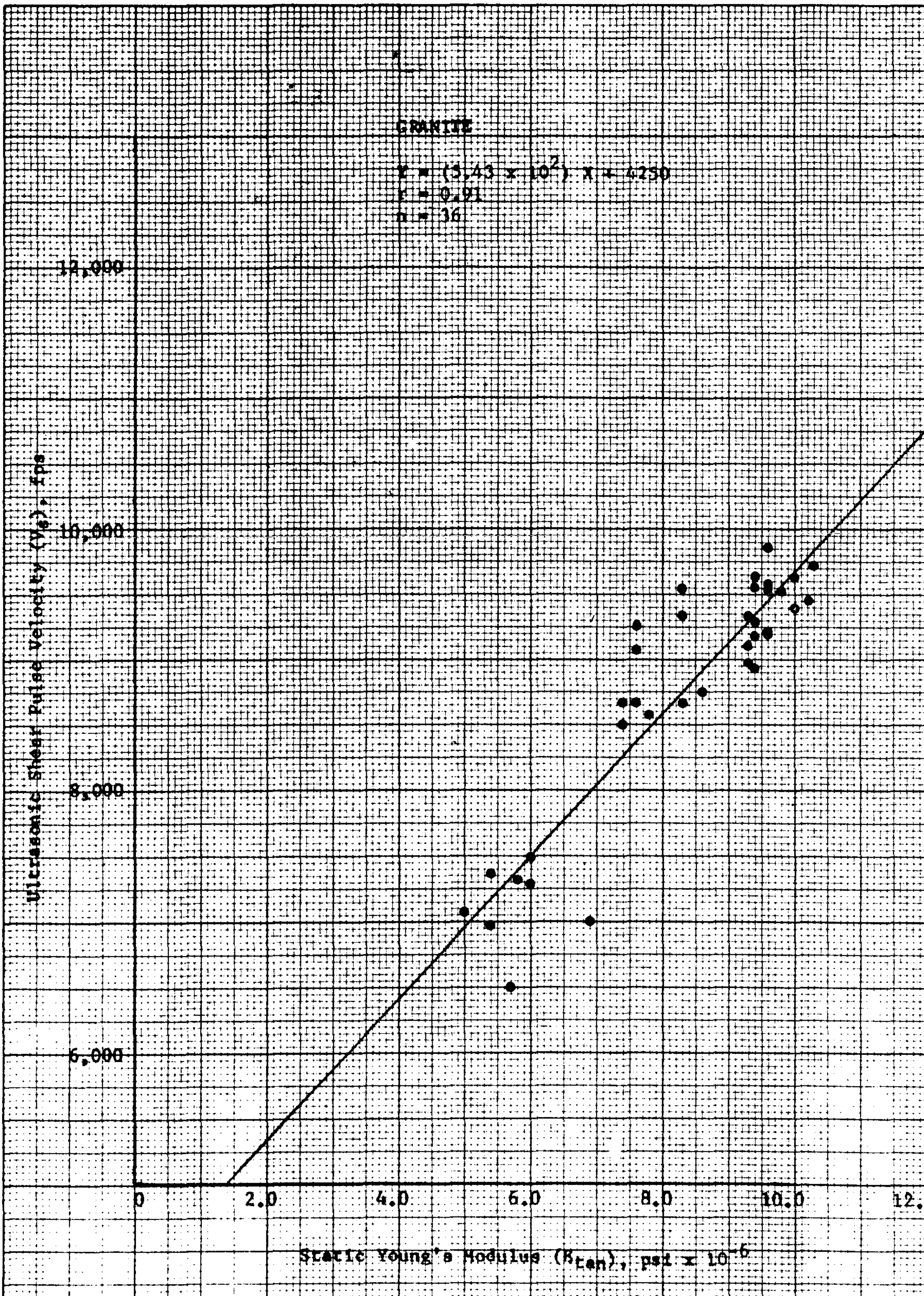
Figure 37


SIERRA NEVADA BATHOLITH TONALITE
Y = (5.35 x 10^2) X + 4370
r = 0.92
n = 21
12,000
10,000
8,000
6,000
0
2.0
4.0
6.0
8.0
10.0
12.0
Ultrasonic Shear Pulse Velocity (Vs), fps
Static Young's Modulus (Etan), psi x 10^-6
Figure 38



TONALITE
Y = (5.38 x 10^2) X + 4350
r = 0.92
n = 35
12,000
10,000
8,000
6,000
Ultrasonic Shear Pulse Velocity (Vs), fps
0
2.0
4.0
6.0
8.0
10.0
12.0
Static Young's Modulus (Etan), psi x 10^-6

Figure 39



GRANITE
Y = (5.43 x 10^2) X + 4250
r = 0.91
n = 36
12,000
10,000
8,000
6,000
Ultrasonic Shear Pulse Velocity (Vs), fps
0
2.0
4.0
6.0
8.0
10.0
12.0
Static Young's Modulus (Etan), psi x 10^-6

Figure 40

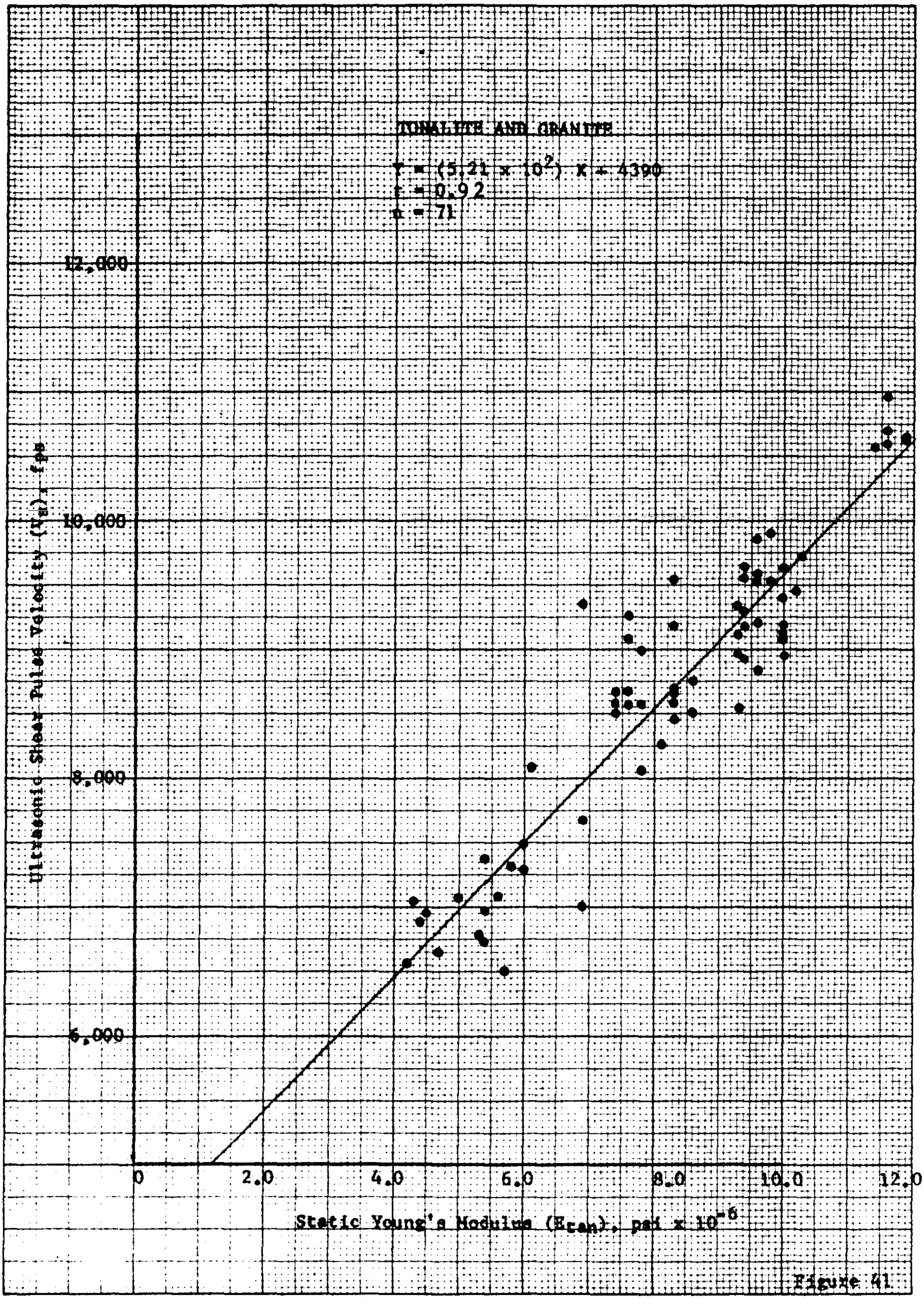

TONALITE AND GRANITE
Y = (5.21 x 10^2) X + 4390
r = 0.92
n = 71
12,000
10,000
8,000
6,000
Ultrasonic Shear Pulse Velocity (V_s), fps
0
2.0
4.0
6.0
8.0
10.0
12.0
Static Young's Modulus (E_tan), psi x 10^-6

Figure 41

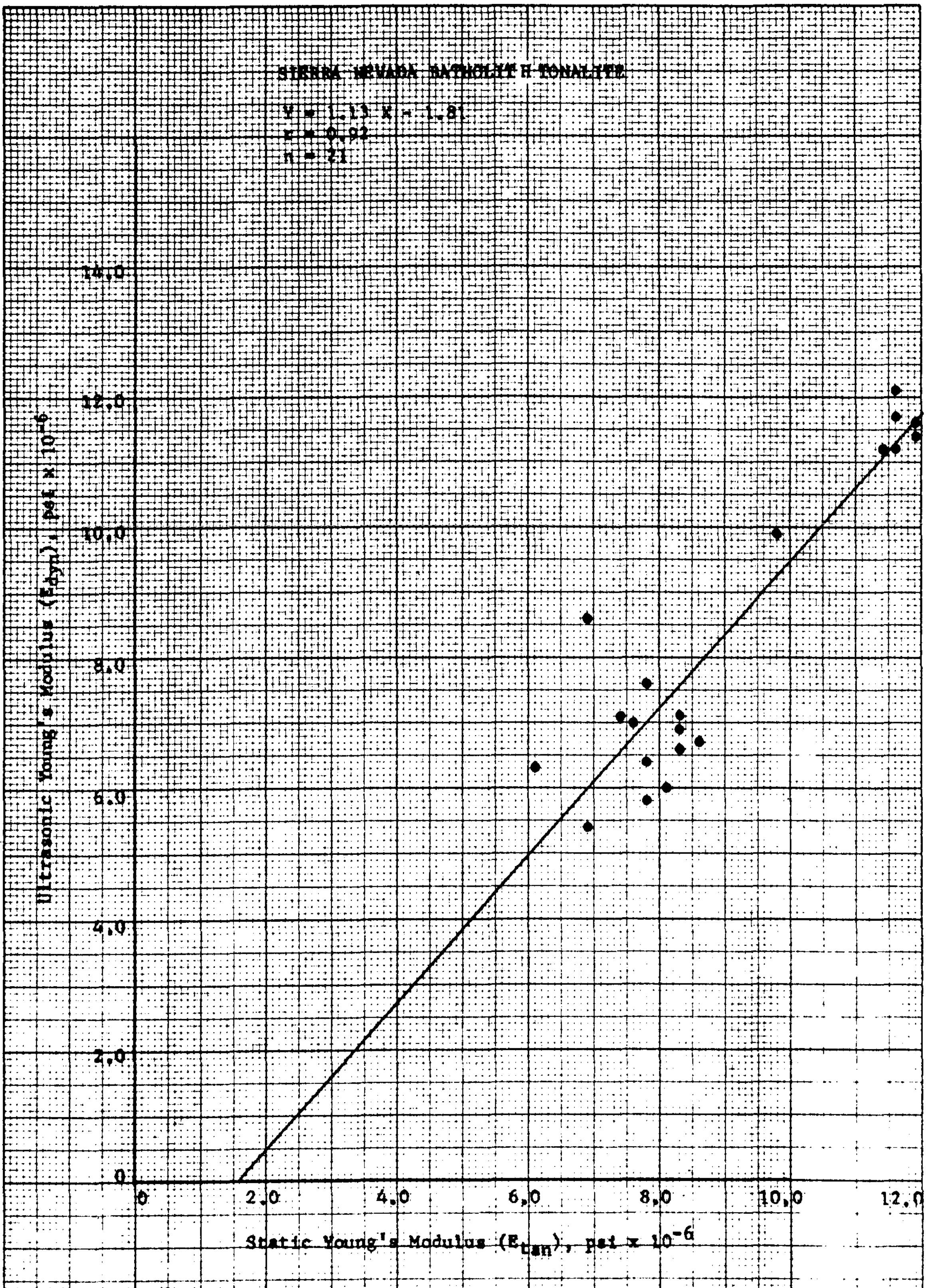
significant (correlation coefficients were much larger than the corresponding critical values as given in Appendix II) and very similar in nature, the quality and orientation of the relationships determined for the granite data alone being very nearly the same as those determined for the tonalite data alone, for comparable pairs of properties. This trend of similarity, which incidentally will be observed to exist generally throughout the correlations of tangent Young's modulus with the other various ultrasonic properties, was somewhat of a reversal of the earlier trend noted for correlations of ultimate uniaxial compressive strength with the various ultrasonic properties wherein the correlations for the granite relationships were frequently insignificant and noticeably inferior to those of the tonalite data. This "change" would appear to be a significant indication that the factors which contribute to ultimate uniaxial compressive strength characteristics and to the nature of the values of tangent Young's modulus of elasticity typical of a particular rock type do not necessarily contribute to the same properties of a similar rock type in the same manner.

A comparison of the scatter diagrams and correlation coefficients (Table 3) determined for the four groups of data representing each pair of physical properties resulted in two additional general observations: (1) correlations determined for the Group 1 and Group 2 tonalite data were similar both in orientation and degree of scatter, reinforcing the previous indication that variation in grain size within the particular rock type, rather than variation in mineral composition and geologic history as allowed within the confines of the specific rock type, was a primary influence upon the degree of scatter typical of the data plots for this rock type, and (2) amalgamation of the data for the tonalites and granites into a single group (Group 4) and correlation of this data as such yielded a scatter diagram and correlation coefficient which were of a nature and quality very similar to those determined for the parent data groups (Groups 2 and 3). This would appear to indicate, for the particular variables being examined, that such an amalgamation of data for such geologically similar rock types would not necessarily result in correlations of a quality substantially lower than the correlations determined for data grouped and correlated by individual rock type.

E_{tan} Versus Ultrasonic Moduli (E_{dyn}, G_{dyn}, K_{dyn}). Scatter diagrams illustrating the general relationships found to exist between tangent Young's modulus of elasticity (E_{tan}) and ultrasonic values of Young's modulus of elasticity (E_{dyn}), shear modulus (G_{dyn}), and bulk modulus (K_{dyn}) are given in Figures 42 through 45, 46 through 49, and 50 through 53, respectively.

Nature and degree of linear correlations obtained for corresponding data groups yielded for all three pairs of variables were quite similar, probably due, as was the case with ultimate uniaxial compressive strength, to similarity in origin of the various values of the three ultrasonic elastic moduli (E_{dyn}, G_{dyn}, and K_{dyn}). All were computed from equations involving values of ultrasonic shear and compressional pulse velocities and specific gravities of the individual specimens.

The physical property correlations determined for those pairs of variables involving ultrasonic moduli were generally quite good.



SIERRA NEVADA BATHOLITH TONALITE
Y = 1.13 X - 1.81
r = 0.92
n = 21
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0
Ultrasonic Young's Modulus (E_dyn), psi x 10^-6
0
2.0
4.0
6.0
8.0
10.0
12.0
Static Young's Modulus (E_tan), psi x 10^-6

Figure 42

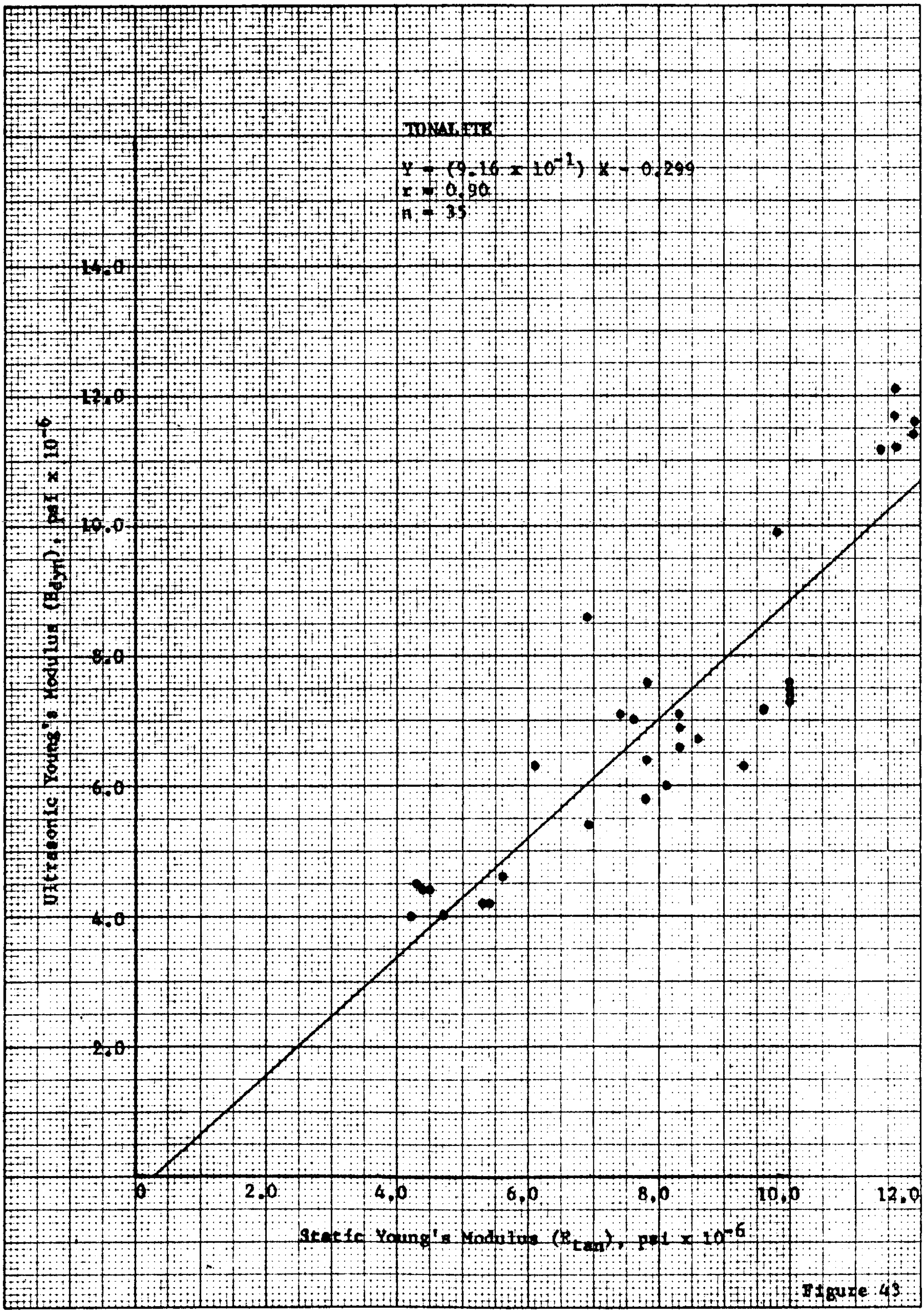

TONALITE
Y = (9.16 x 10^-1) X - 0.299
r = 0.90
n = 35
Ultrasonic Young's Modulus (E_dyn), psi x 10^-6
Static Young's Modulus (E_tan), psi x 10^-6
0
2.0
4.0
6.0
8.0
10.0
12.0
14.0

Figure 43

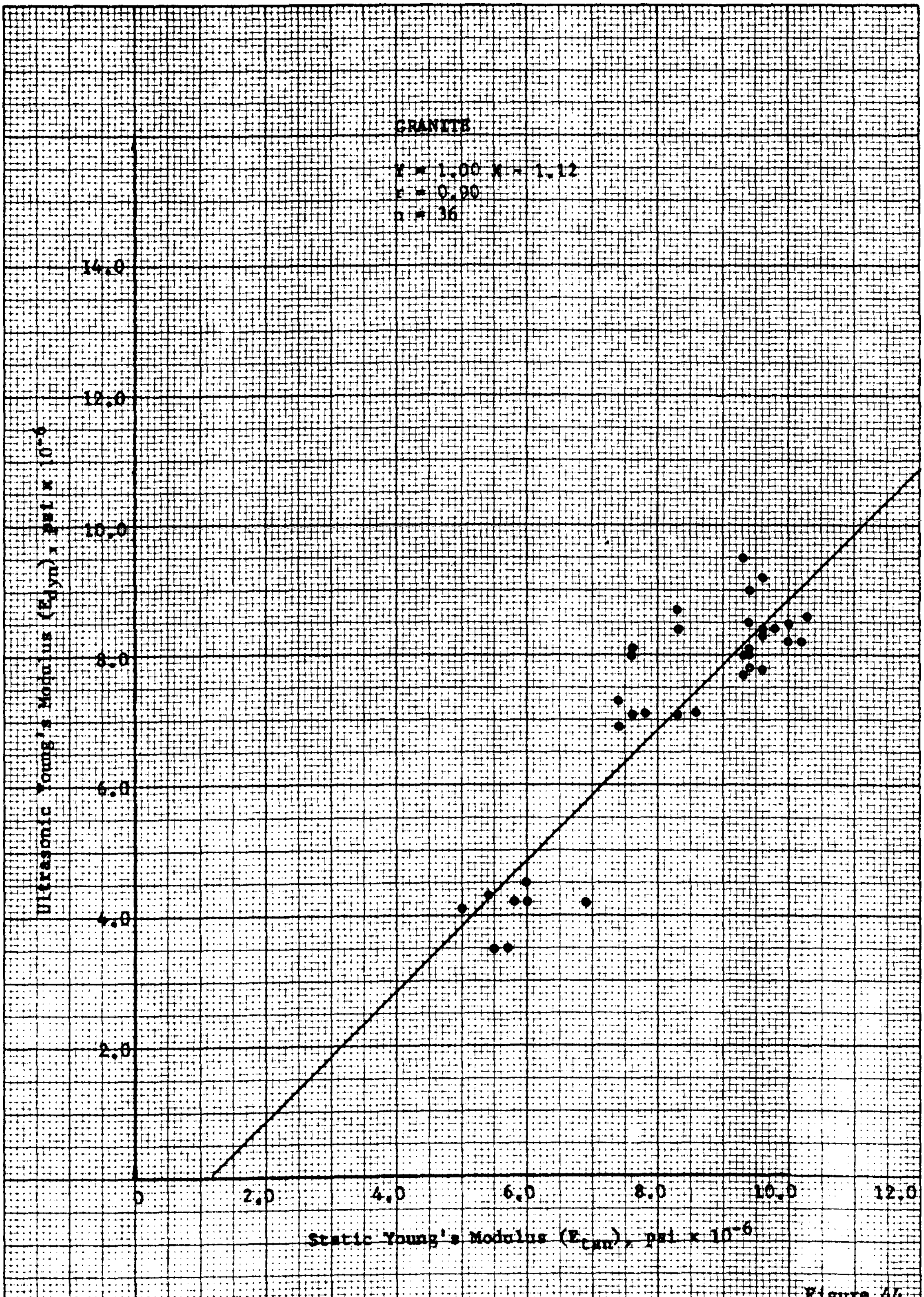

GRANITE
Y = 1.00 X - 1.12
r = 0.90
n = 36
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0
2.0
4.0
6.0
8.0
10.0
12.0
Ultrasonic Young's Modulus (E_{dyn}), psi x 10^{-6}
Static Young's Modulus (E_{tan}), psi x 10^{-6}

Figure 44

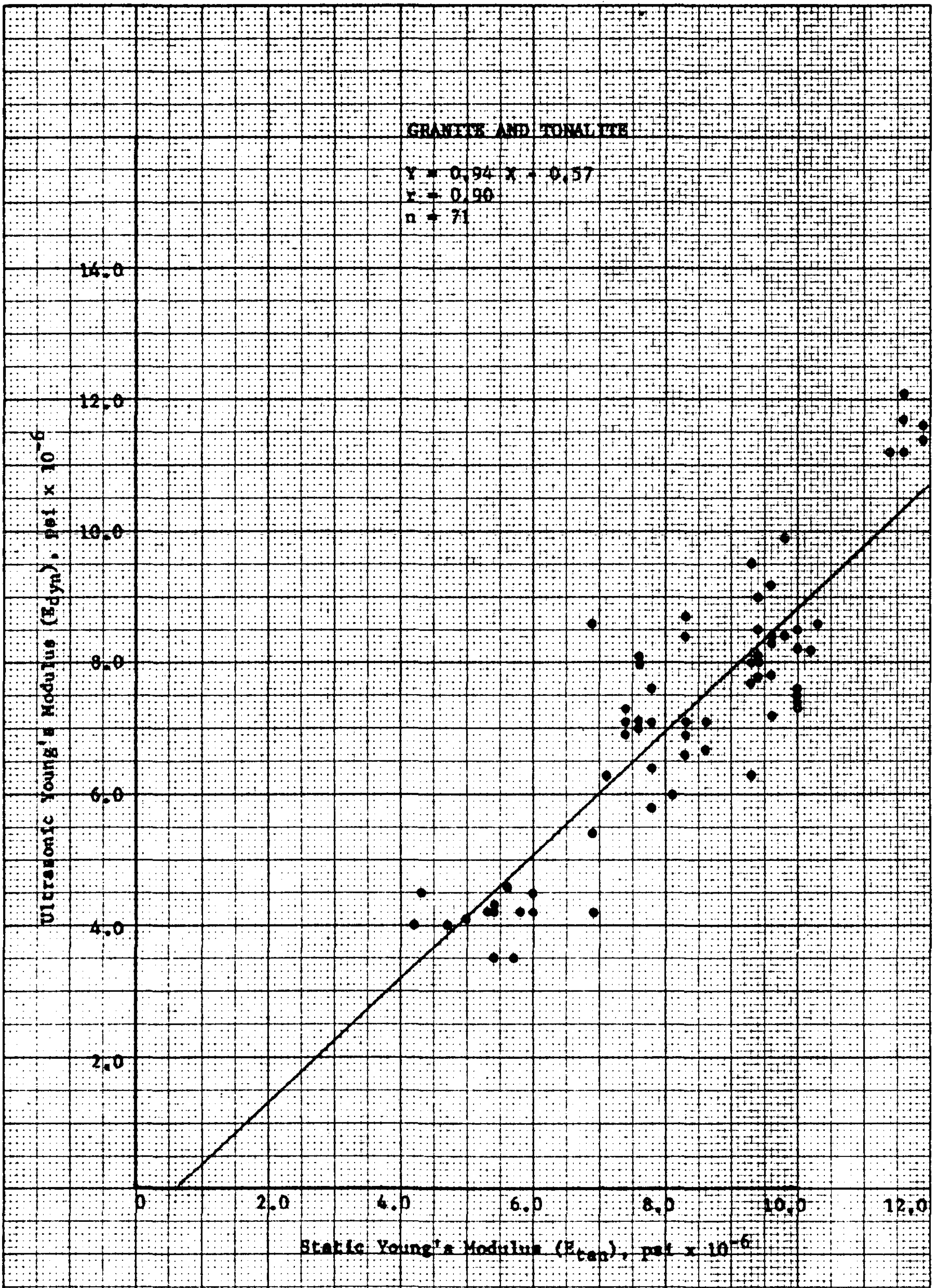
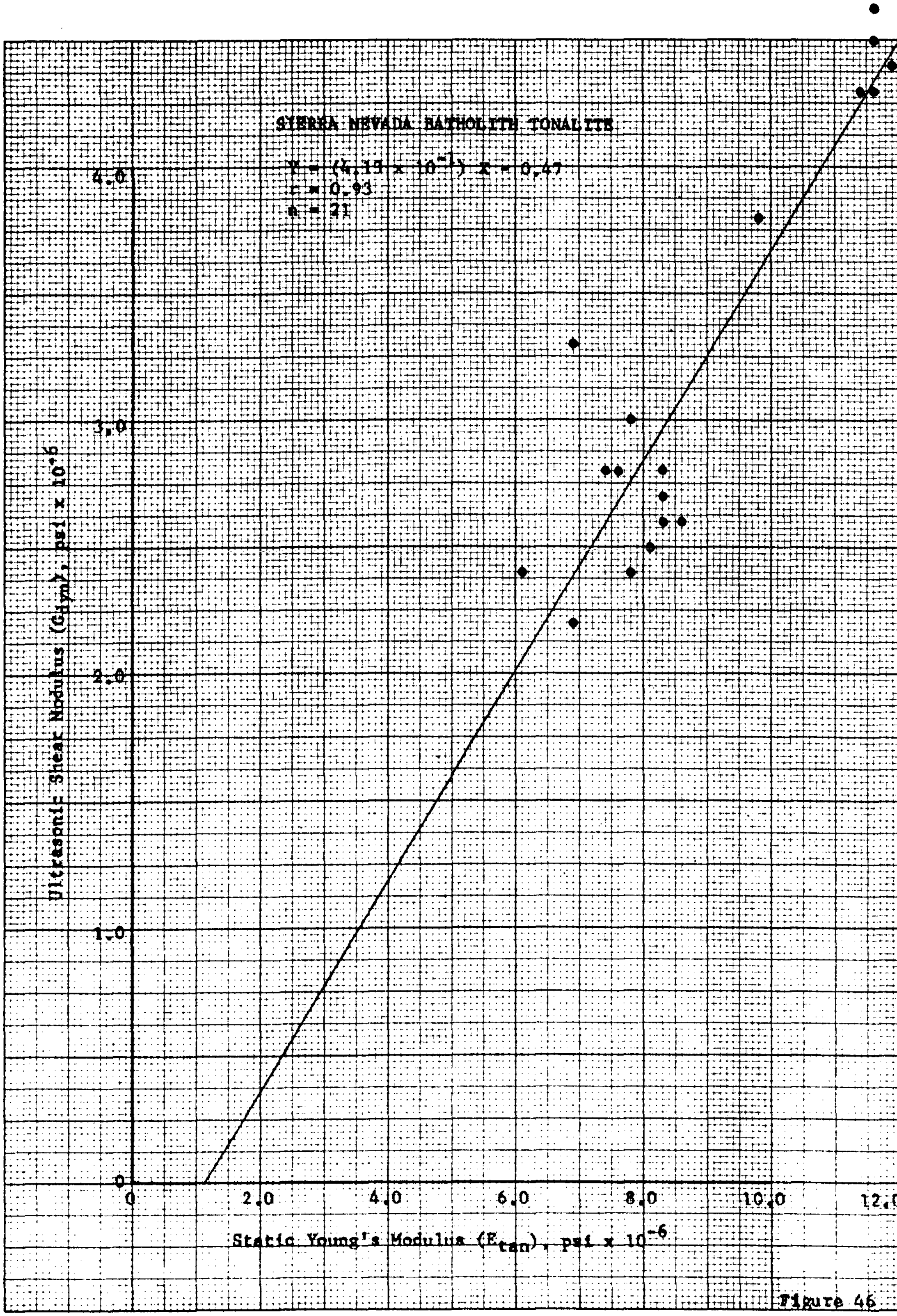
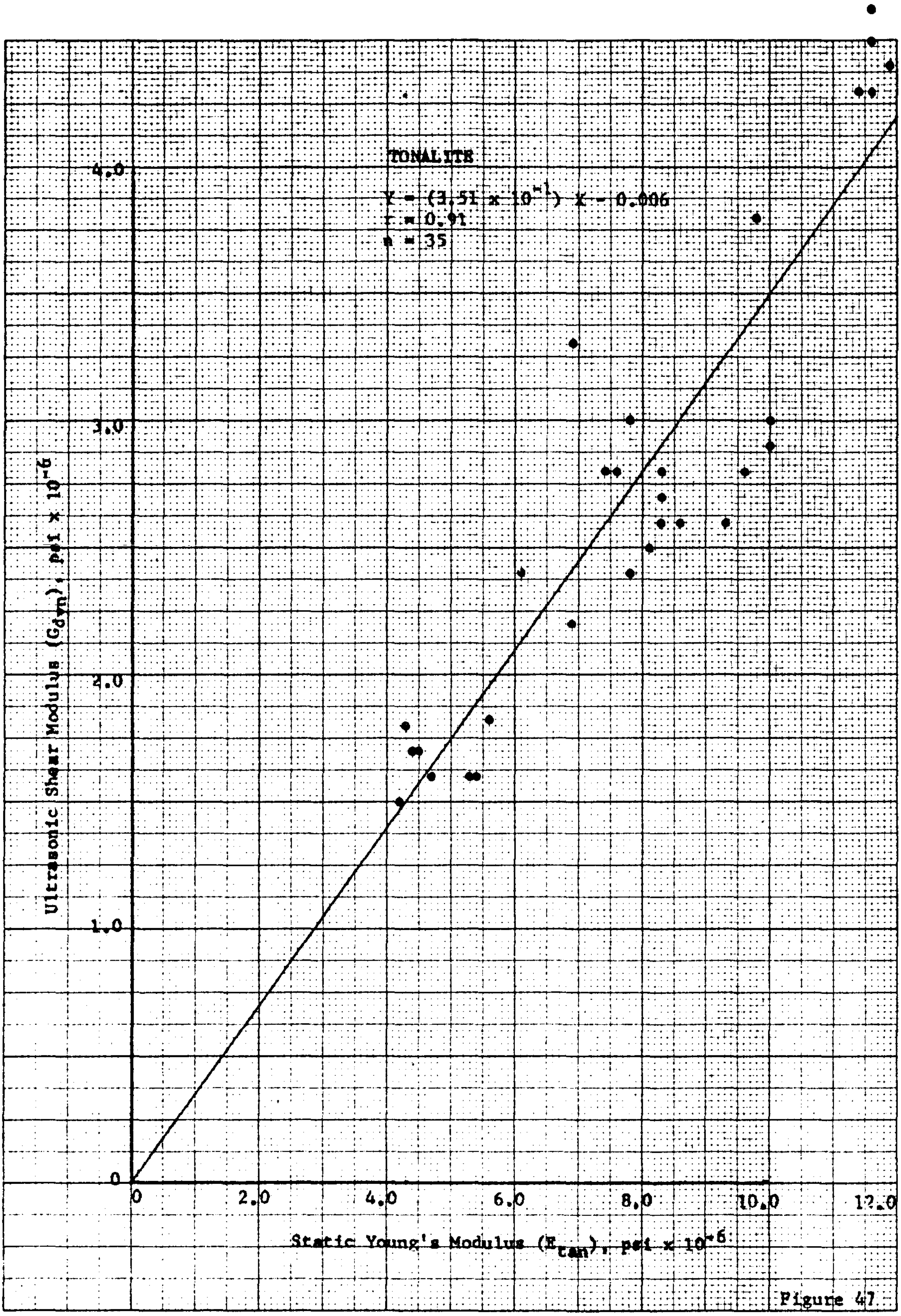

GRANITE AND TONALITE
Y = 0.94 X + 0.57
r = 0.90
n = 71
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0
2.0
4.0
6.0
8.0
10.0
12.0
Ultrasonic Young's Modulus (Edyn), psi x 10-6
Static Young's Modulus (Etan), psi x 10-6

Figure 45



SIERRA NEVADA BATHOLITH TONALITE
Y = (4.15 x 10^-1) X - 0.47
r = 0.93
n = 21
4.0
3.0
2.0
1.0
0
0
2.0
4.0
6.0
8.0
10.0
12.0
Ultrasonic Shear Modulus (Gdyn), psi x 10^-6
Static Young's Modulus (Etan), psi x 10^-6

Figure 46


TONALITE
Y = (3.51 x 10⁻¹) X - 0.006
r = 0.91
n = 35
4.0
3.0
2.0
1.0
0
Ultrasonic Shear Modulus (G_dyn), psi x 10⁻⁶
0
2.0
4.0
6.0
8.0
10.0
12.0
Static Young's Modulus (E_tan), psi x 10⁻⁶
Figure 47

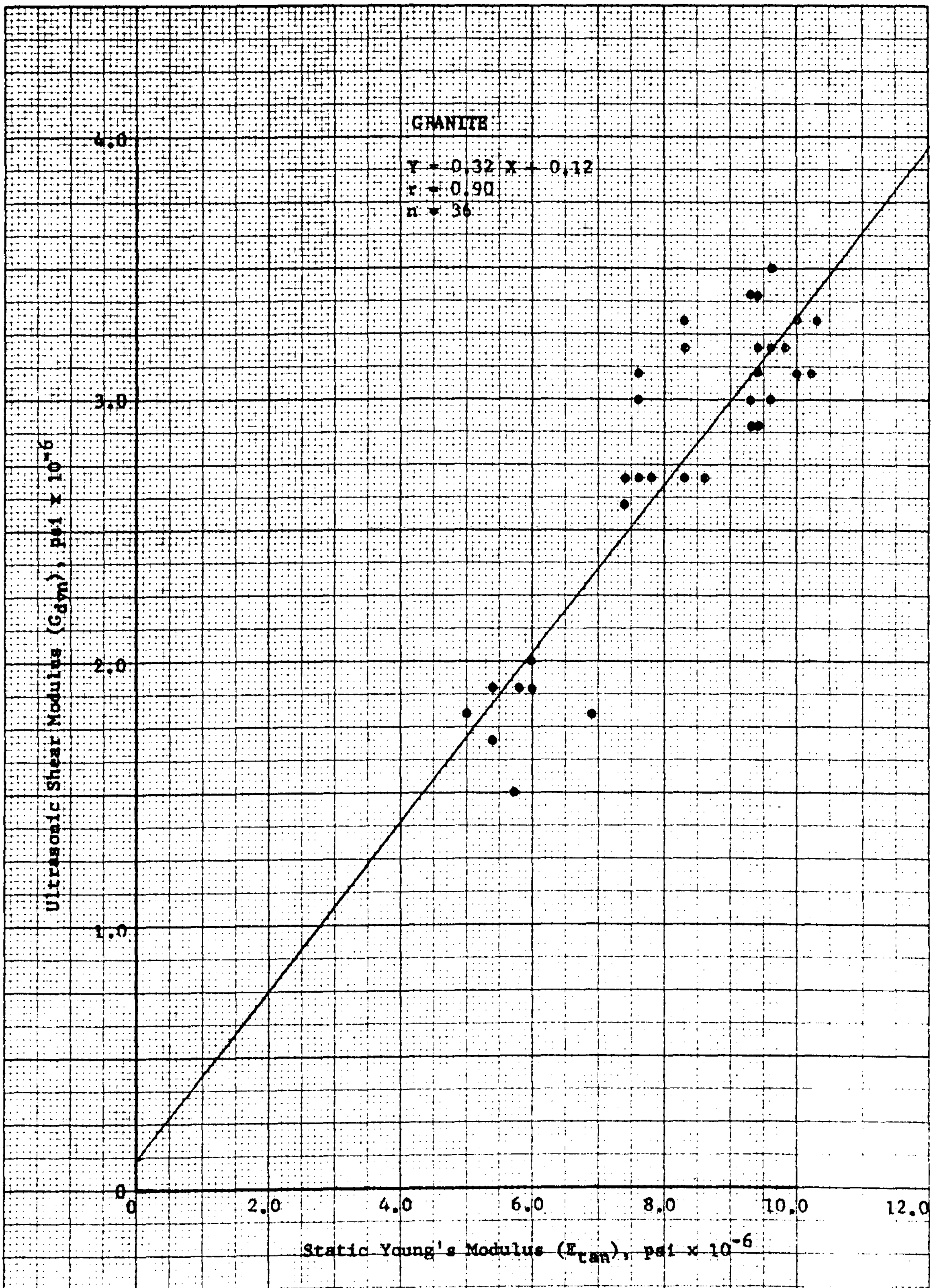
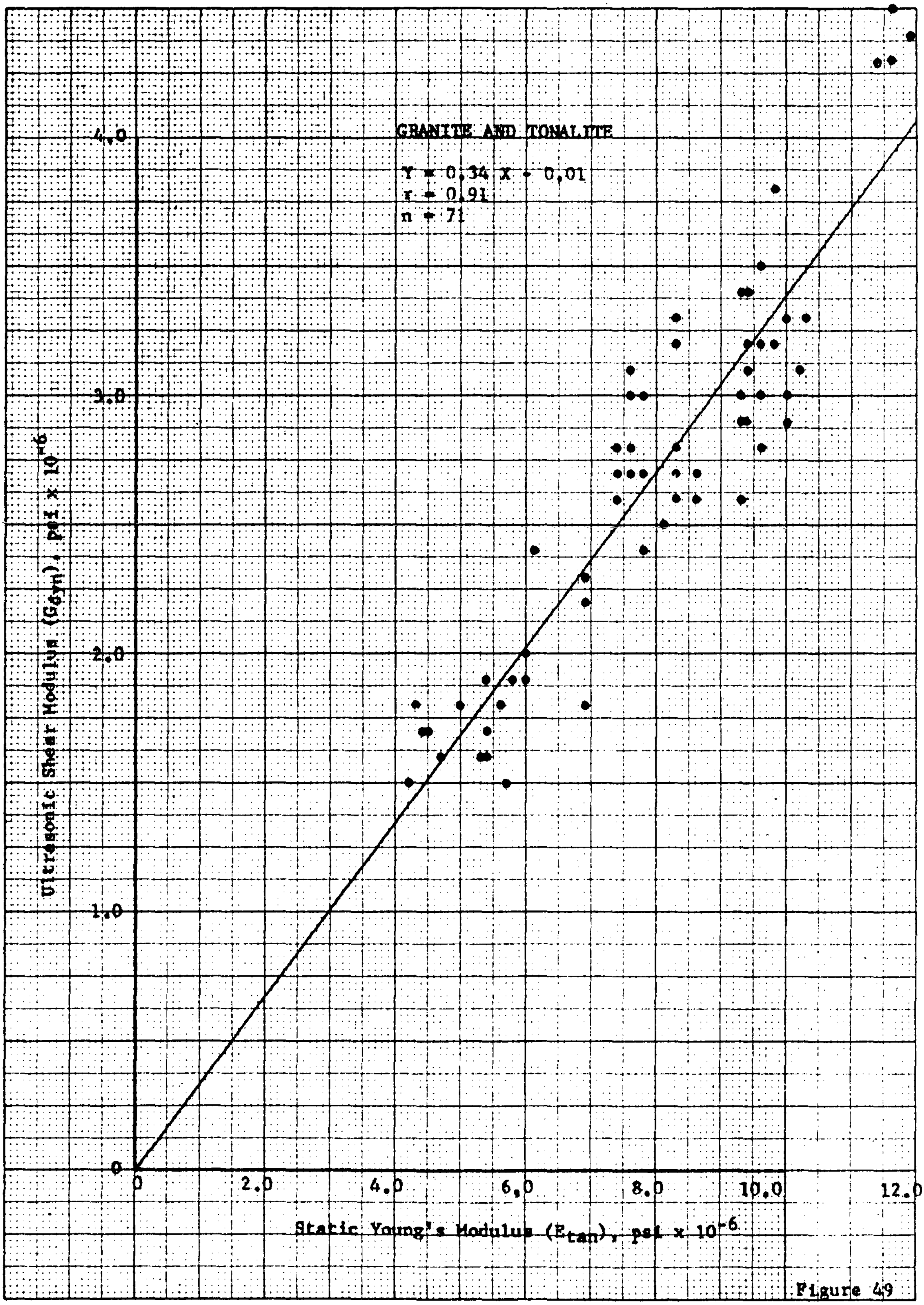
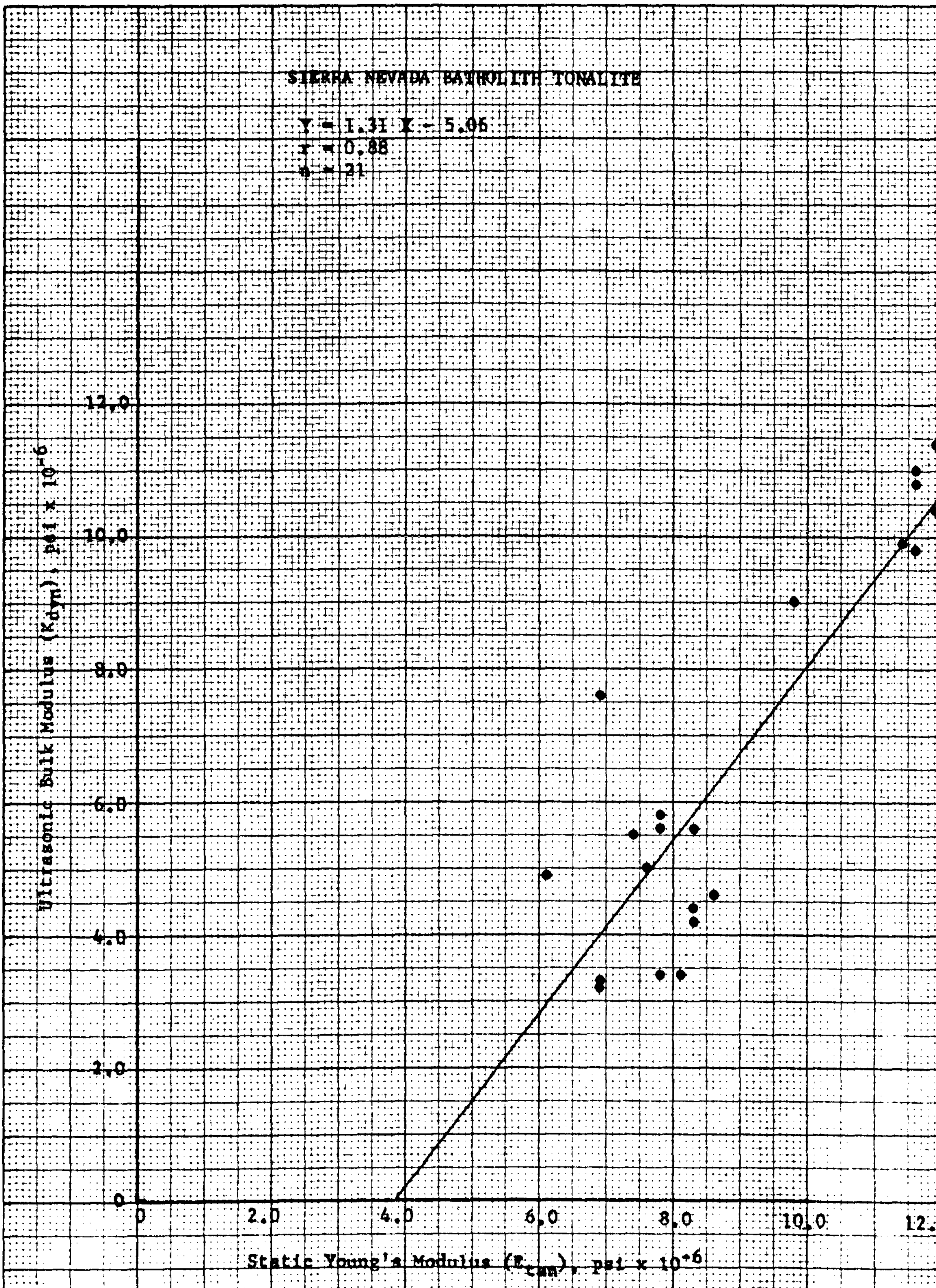

GRANITE
Y = 0.32 X + 0.12
r = 0.90
n = 36
4.0
3.0
2.0
1.0
0
0
2.0
4.0
6.0
8.0
10.0
12.0
Ultrasonic Shear Modulus (G_{dyn}), psi x 10^{-6}
Static Young's Modulus (E_{tan}), psi x 10^{-6}

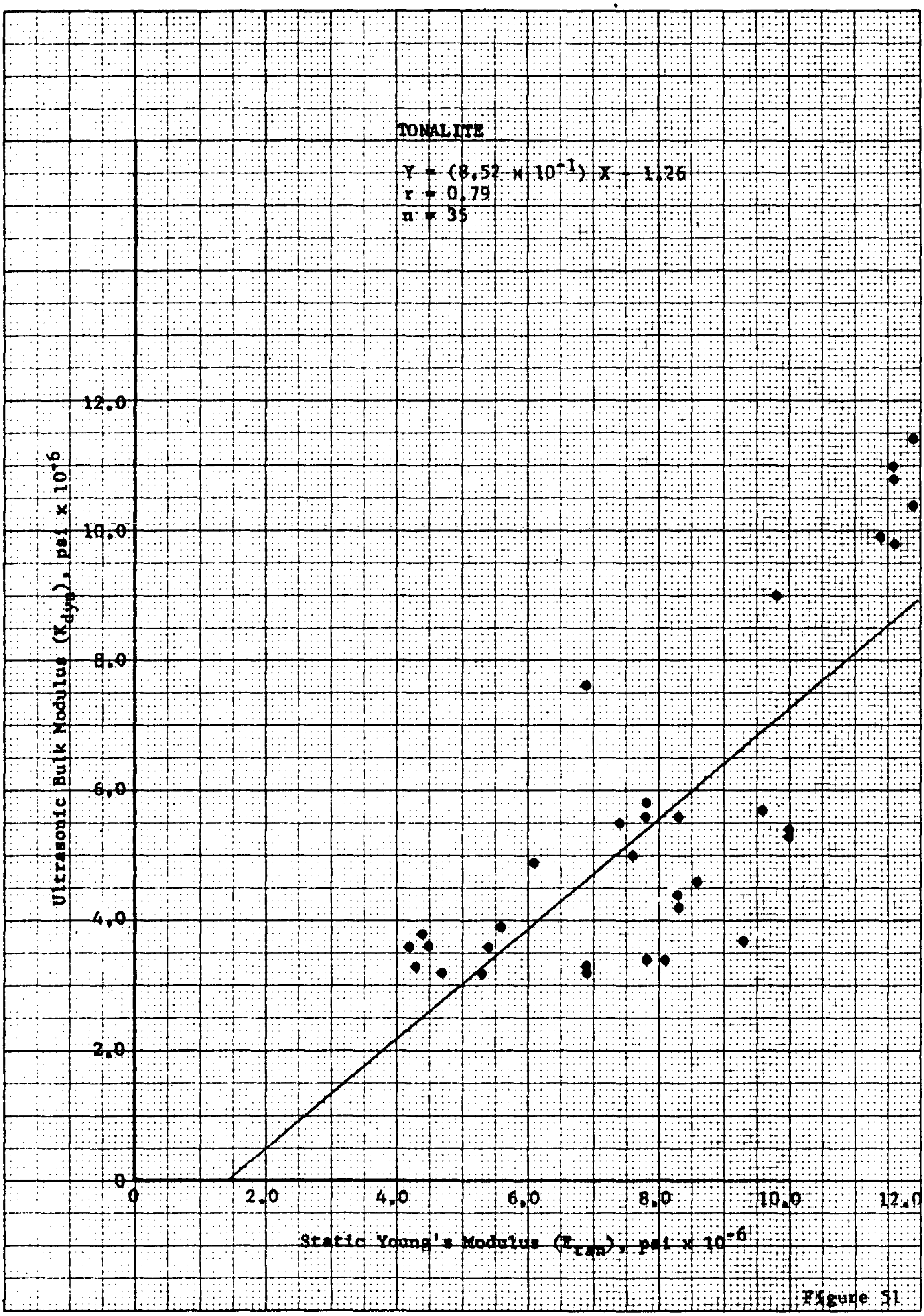
Figure 48

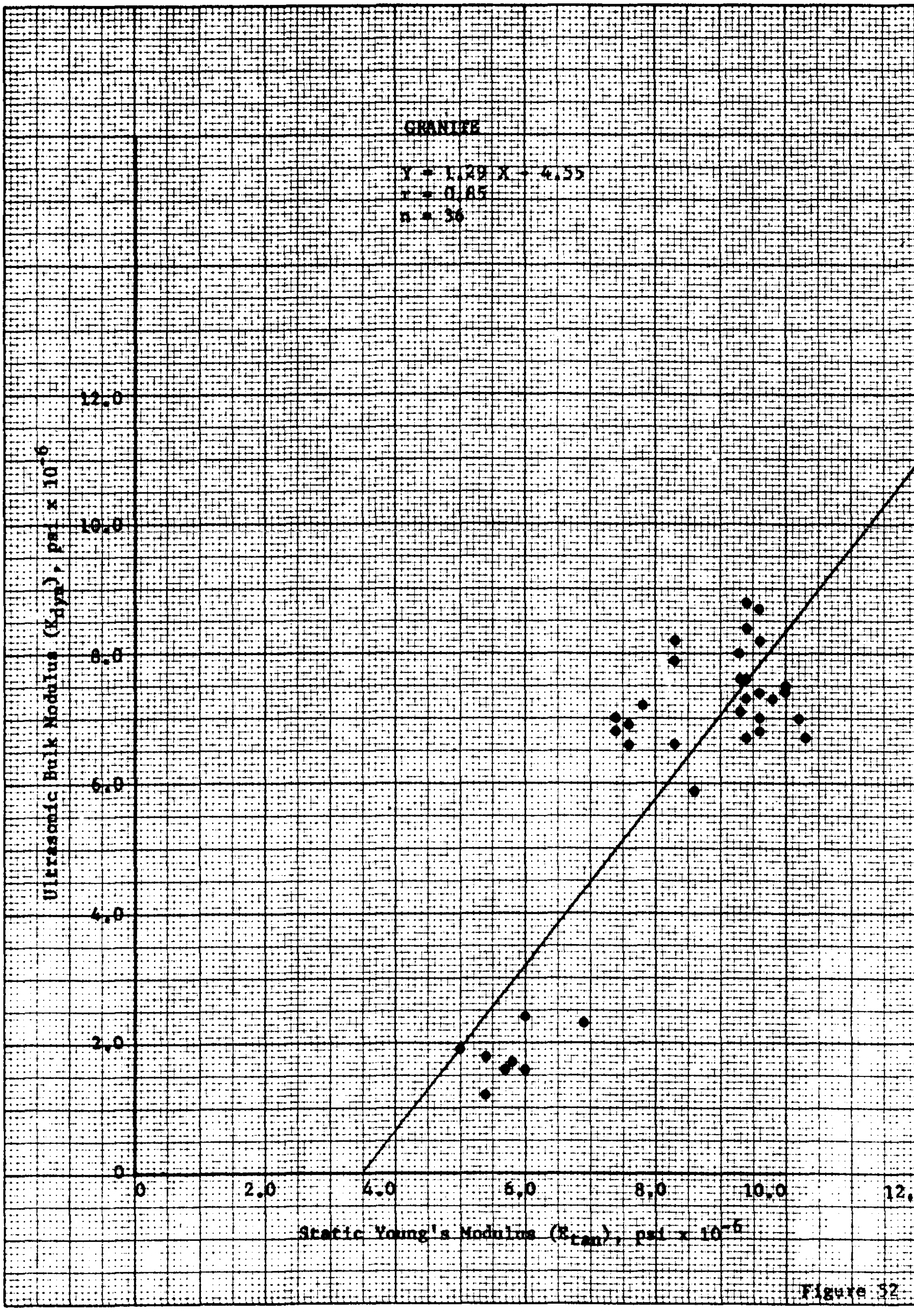

GRANITE AND TONALITE
Y = 0.34 X + 0.01
r = 0.91
n = 71
Ultrasonic Shear Modulus (Gdyn), psi x 10-6
Static Young's Modulus (Etan), psi x 10-6
0
1.0
2.0
3.0
4.0
0
2.0
4.0
6.0
8.0
10.0
12.0
Figure 49



SIERRA NEVADA BATHOLITH TONALITE
Y = 1.31 X - 5.06
r = 0.88
n = 21
Ultrasonic Bulk Modulus (K_{dyn}), psi x 10^{-6}
12.0
10.0
8.0
6.0
4.0
2.0
0
0
2.0
4.0
6.0
8.0
10.0
12.0
Static Young's Modulus (E_{tan}), psi x 10^{-6}

Figure 50


TONALITE
Y = (8.52 x 10-1) X - 1.26
r = 0.79
n = 35
Ultrasonic Bulk Modulus (Kdyn), psi x 10-6
12.0
10.0
8.0
6.0
4.0
2.0
0
0
2.0
4.0
6.0
8.0
10.0
12.0
Static Young's Modulus (Etan), psi x 10-6
Figure 51



GRANITE
Y = 1.29 X - 4.55
r = 0.85
n = 36
Ultrasonic Bulk Modulus (K_dyn), psi x 10^-6
12.0
10.0
8.0
6.0
4.0
2.0
0
0
2.0
4.0
6.0
8.0
10.0
12.0
Static Young's Modulus (E_tan), psi x 10^-6

Figure 52

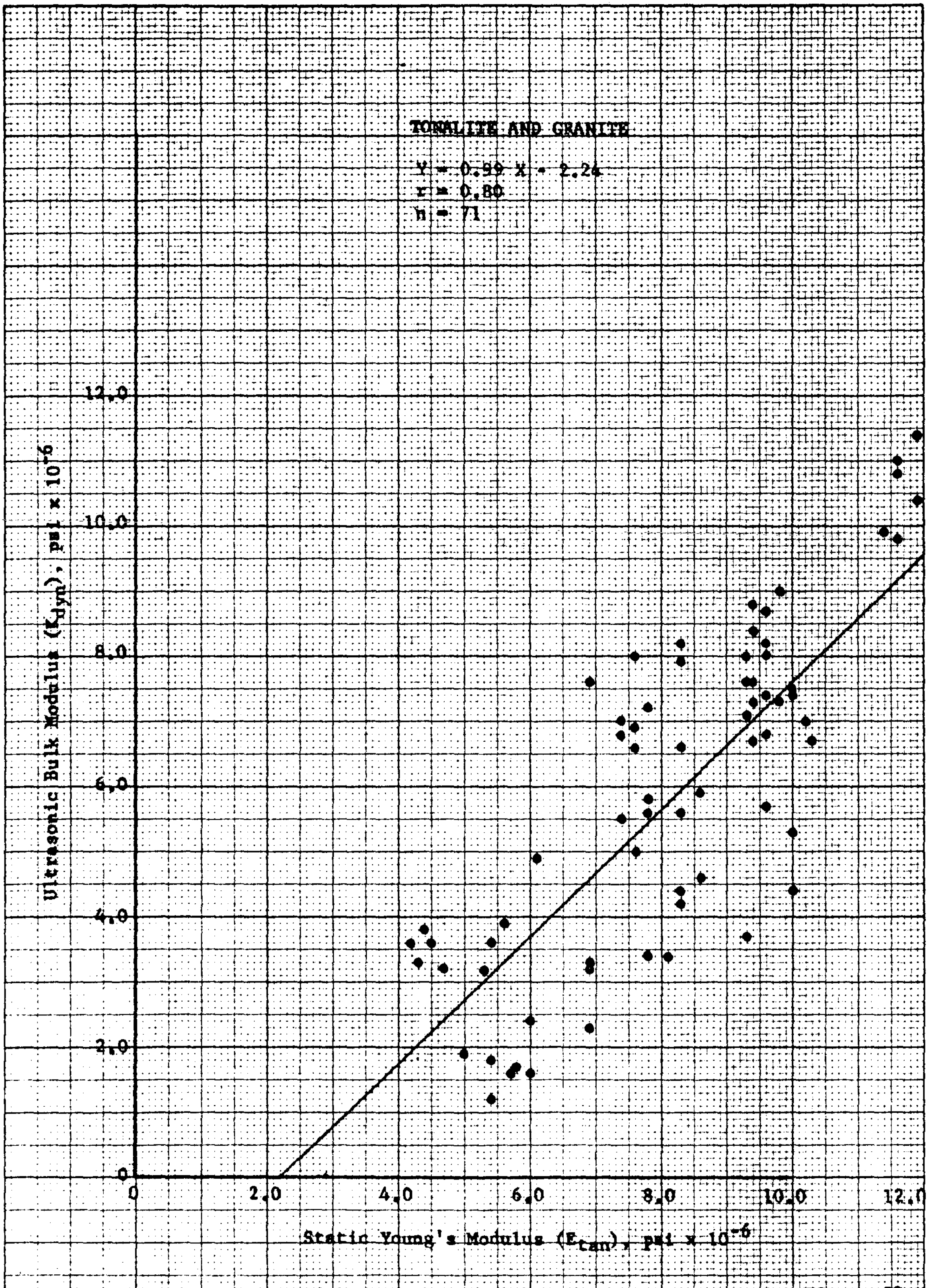

TONALITE AND GRANITE
Y = 0.99 X - 2.24
r = 0.80
n = 71
Ultrasonic Bulk Modulus (K_{dyn}), psi x 10^{-6}
12.0
10.0
8.0
6.0
4.0
2.0
0
0
2.0
4.0
6.0
8.0
10.0
12.0
Static Young's Modulus (E_{tan}), psi x 10^{-6}

Figure 53

Correlation coefficients determined for two of these pairs (E_{tan} versus E_{dyn} and E_{tan} versus G_{dyn}) were among the highest yielded by correlation of any of the pairs of variables examined during the course of this investigation (Table 3). These two groups of correlations were not sufficiently superior to those involving the easier to determine values of shear and compressional pulse velocity, however, to alone justify the additional time and money which is necessary to the computation of ultrasonic elastic moduli. This is not to say, however, that computation of ultrasonic moduli might not be desirable for purposes other than physical property correlations.

The general trends characteristic of the physical property correlations discussed in the section immediately prior to this one (E_{tan} versus V_p and V_s) were also noted to exist for these correlations. Specifically, degrees of correlation determined for the Group 1 tonalite data groups were only slightly larger in magnitude than those yielded by the Group 2 tonalite data groups for corresponding pairs of physical properties, substantiating previous indications that variation in grain size, as opposed to significant variation in mineral composition and geologic history as allowed within the confines of a specific rock type, appears to be of primary significance in the determination of the degree of scatter typical of various physical property correlations within the particular rock type.

As was mentioned in the previous section, combination of the data for both rock types, granite and tonalite, into a single statistical sample and correlation of this single mass of data did not, for either of the three pairs of physical properties considered in this section, result in an appreciable sacrifice in quality of the correlations obtained for the granite data alone or the tonalite data alone. Thus, for these pairs of physical properties and these rock types, variation in rock type appeared to have no significant effect on the quality of the correlations obtained.

E_{tan} Versus ν_{dyn}. Figures 54 through 57 graphically illustrate the general lack of linear association observed to exist between tangent Young's modulus of elasticity and ultrasonic Poisson's ratio.

Correlation coefficients determined for this pair of variables (four data groups) were, in most cases, appreciably larger than the ones obtained for the plots of ultimate uniaxial compressive strength versus Poisson's ratio. Examination of the scatter plots (Figures 54 through 57), however, revealed no significant trends to exist between the two variables. The higher correlation coefficient (yielded by the Group 3 data) had resulted solely from the location of eight data points, in this instance, points of questionable validity (values of Poisson's ratio were felt to be unrepresentative) in a manner so as to give definite orientation to the least-squares line without increasing the quality of the plot to one of actual significance (See Figure 56).

Thus, as was the case with the correlation of ultimate uniaxial compressive strength with ultrasonic Poisson's ratio, the correlations determined for tangent Young's modulus of elasticity versus ultrasonic Poisson's ratio were all of little or no practical value from a property prediction point of view.

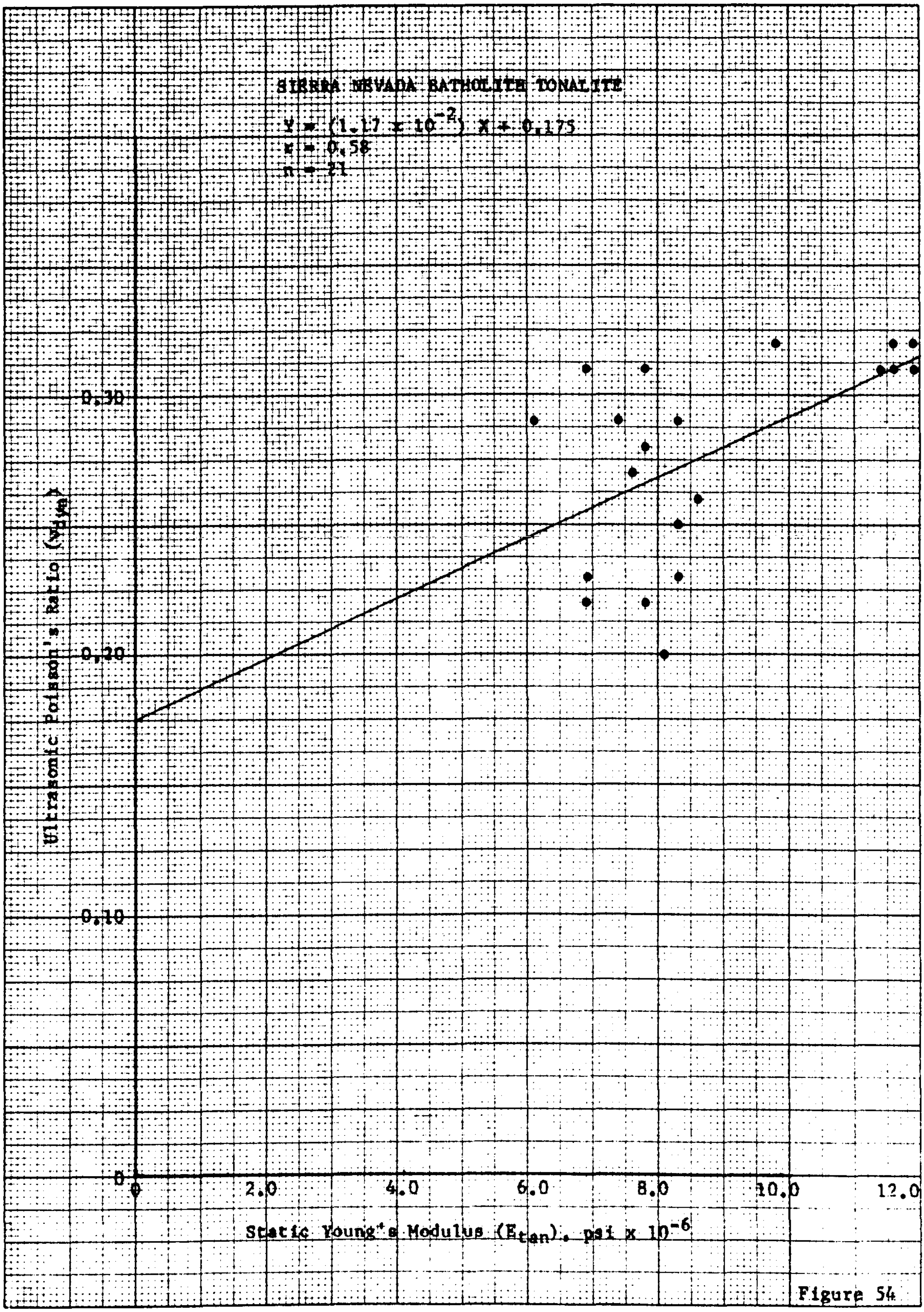

SIERRA NEVADA BATHOLITE TONALITE
Y = (1.17 x 10^-2) X + 0.175
r = 0.58
n = 21
Ultrasonic Poisson's Ratio (νdyn)
0.30
0.20
0.10
0
0
2.0
4.0
6.0
8.0
10.0
12.0
Static Young's Modulus (Etan), psi x 10^-6

Figure 54

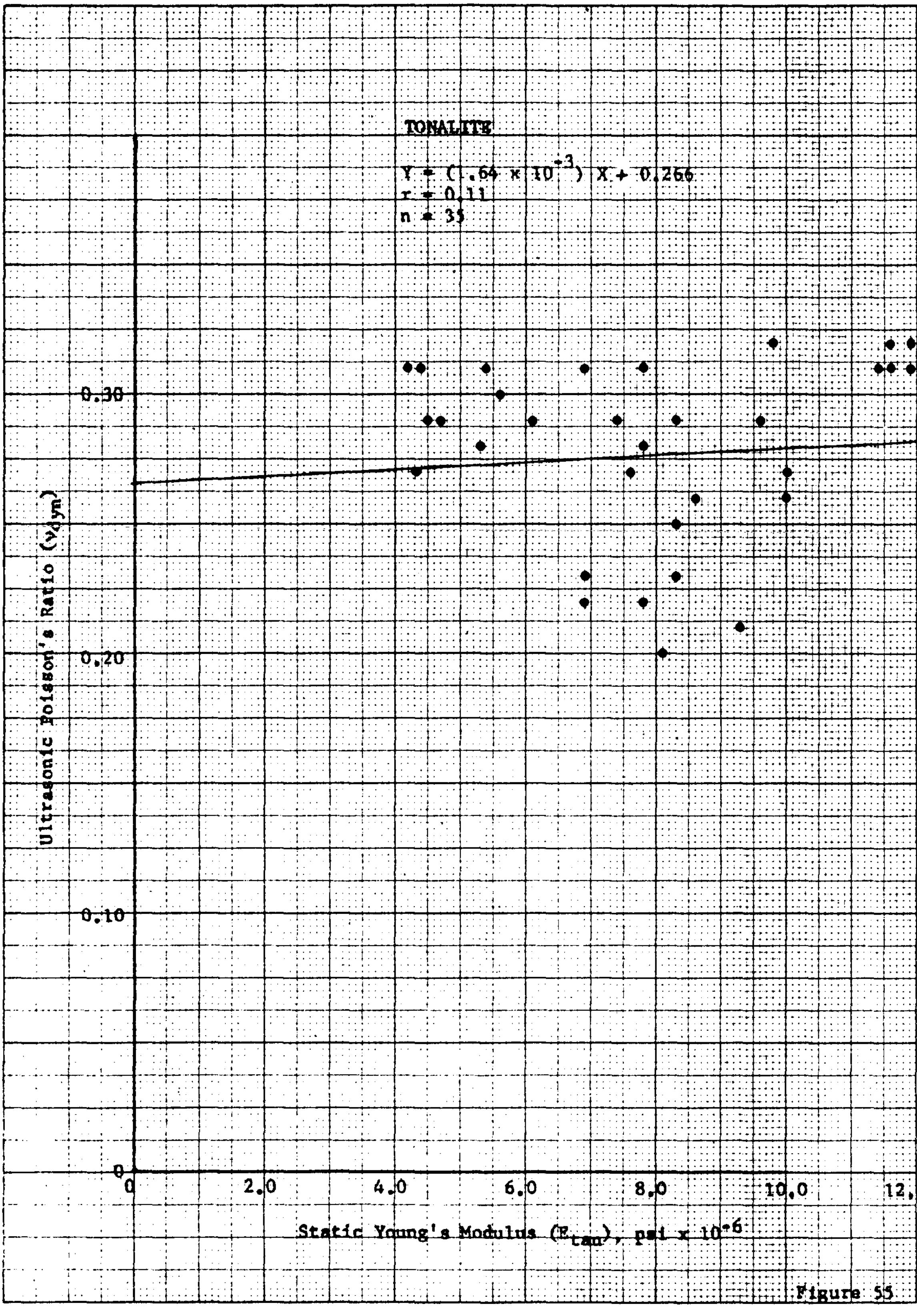
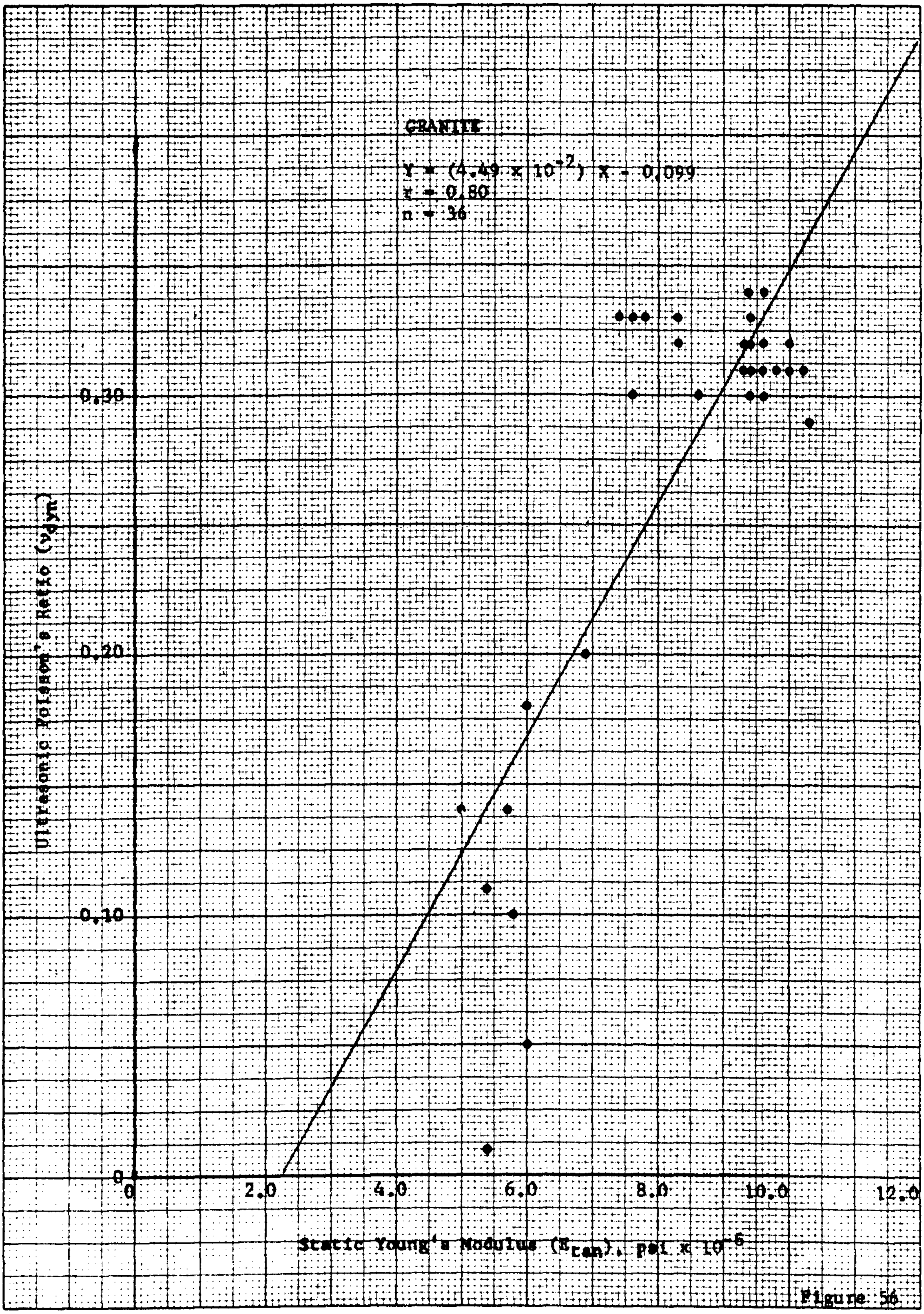

TONALITE
Y = (1.64 x 10⁻³) X + 0.266
r = 0.11
n = 35
0.30
0.20
0.10
0
Ultrasonic Poisson's Ratio (ν_dyn)
0
2.0
4.0
6.0
8.0
10.0
12.0
Static Young's Modulus (E_tan), psi x 10⁻⁶

Figure 55


GRANITE
Y = (4.49 x 10^-2) X - 0.099
r = 0.80
n = 36
Ultrasonic Poisson's Ratio (v_dym)
0.30
0.20
0.10
0
0
2.0
4.0
6.0
8.0
10.0
12.0
Static Young's Modulus (E_tan), psi x 10^-6
Figure 56

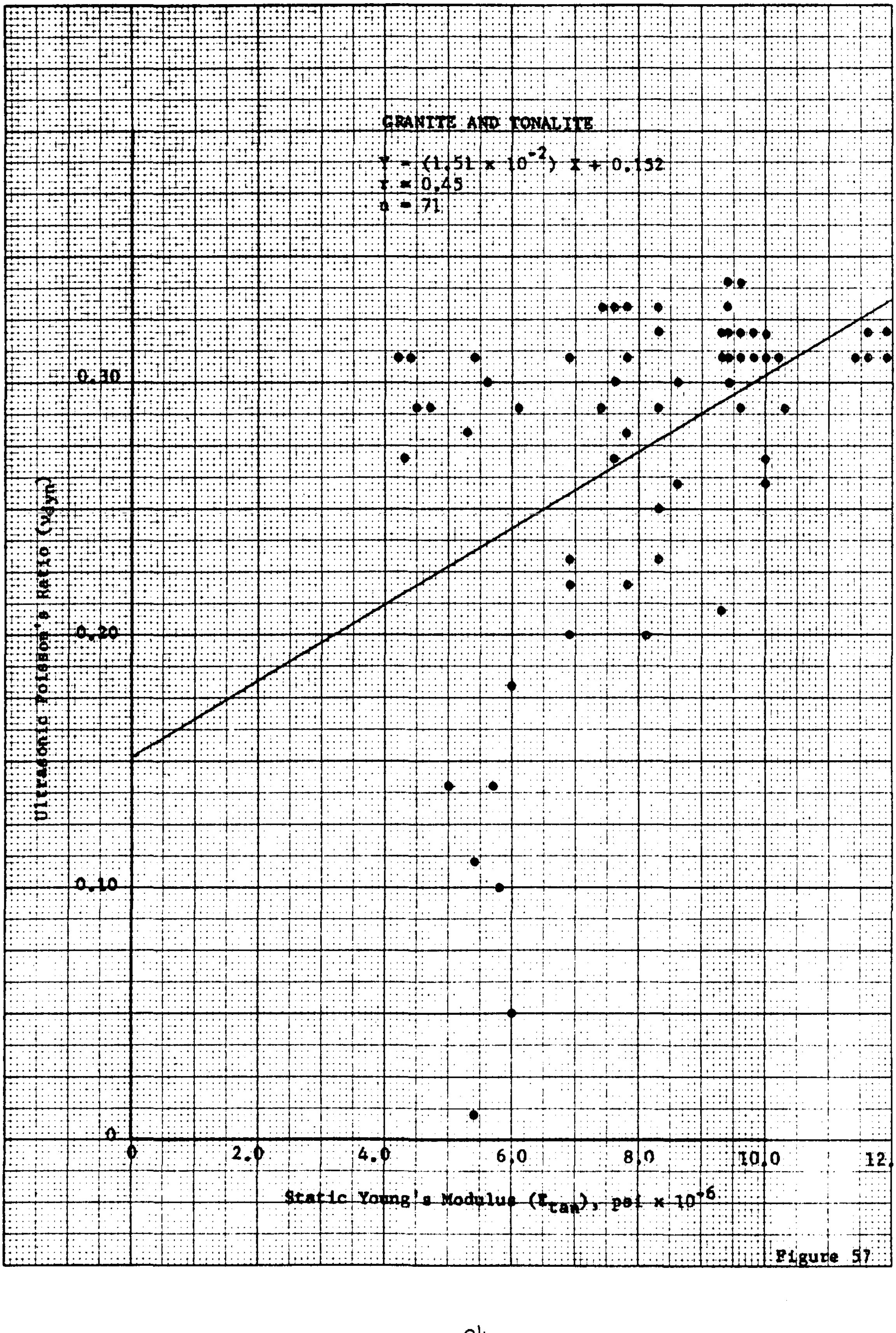

GRANITE AND TONALITE
Y = (1.51 x 10^-2) X + 0.152
r = 0.45
n = 71
0.30
0.20
0.10
0
Ultrasonic Poisson's Ratio (νdyn)
0
2.0
4.0
6.0
8.0
10.0
12.0
Static Young's Modulus (Etan), psi x 10^-6

Figure 57

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Based upon results of the physical property tests conducted during this investigation, and on linear correlations of the various physical properties determined for these granites and tonalites, the following conclusions appear justified.

(a) Variation in grain size rather than substantial variation in percentage mineral composition and geologic history as allowed within the confines of the specific rock type (tonalite) appears to be the primary factor responsible for the degree of scatter typical of data plots for the various pairs of physical rock properties examined for a specific intact rock type. It must be kept in mind, however, that the two rock types used in this investigation were both intrusive igneous rocks and were essentially of a homogeneous and isotropic nature. Thus, the above conclusion should be restricted basically to igneous rocks. It is felt that variation in geologic history would have substantial influence on the degree of scatter typical of rock property correlations for metamorphic and sedimentary rocks, particularly where there are wide variations in angles of inclination of planes of shistosity and sedimentation, and in degrees of cementation and recrystalization.

(b) Variation in rock type appears to have a generally undesirable influence on the quality of the correlation obtained for various pairs of rock properties. Where correlations between two particular physical properties determined for various individual rock types are quite different in degree of linear association, amalgamation of the smaller individual correlations into a single larger relationship inevitably results in a sacrifice of quality and usefullness of the good relationships due to introduction of data exhibiting lesser degrees of correlation. This type of situation was found to exist when the corresponding Group 2 and Group 3 correlations which involved ultimate uniaxial compressive strength as one variable were combined and evaluated as single groups (Group 4). A similar situation would result if the various physical property correlations for the individual rock types were of a differing nature (inclination or orientation) such that amalgamation of the individual correlations for a single pair of properties into one large group would produce a large degree of scatter and thus a lesser degree of linear association. This would probably be more likely to occur when greatly different rock types were involved.

(c) A comparison of linear correlations involving ultrasonic pulse velocities with those involving ultrasonic elastic moduli indicated that linear relationships in which either ultrasonic shear moduli or ultrasonic Young's moduli were employed as one variable were slightly superior in quality to similar relationships in which one of the ultrasonic pulse velocities was involved. The degree of superiority did not appear great enough, however, to alone warrant the additional time and effort necessary to the determination of the ultrasonic elastic constants.

(d) Correlations which employ ultrasonic shear pulse velocity as one variable appear to be superior in quality to similar correlations involving ultrasonic compressional pulse velocity as one variable. Shear pulse velocity appears to be the ultrasonic physical property of those examined in this study, which offers the best possibility for linear correlation with and preliminary prediction of ultimate uniaxial compressive strength and tangent (static) Young's modulus of elasticity.

(e) It does not appear likely that ultrasonic values of Poisson's ratio have any appreciable value in the area rock property correlation and prediction.

Recommendations

As indicated previously, this investigation was confined to two types of igneous rocks. It is suggested that several varieties of metamorphic and sedimentary rocks be studied in a similar manner to determine whether or not the trends observed in this investigation are typical of all rocks or are merely typical of igneous rock types. In particular, the effects of variation in grain size on the degree of scatter typical of physical property correlations for metamorphic and sedimentary rocks should be investigated, as it is felt that variation geologic history may here be of primary importance rather than variation in grain size.

An investigation should be made to determine the extent to which physical property relations such as those investigated here might be better represented by curvilinear correlations rather than linear correlations. Several of the scatter diagrams in this study appeared to be of a nature that might be better represented by a second degree curve. In addition, a more extensive statistical analysis (determine confidence limits, etc.) might be performed to determine the practical value of such physical property correlations for property prediction purposes.

Ultrasonic shear pulse velocity and ultrasonic shear modulus should be more thoroughly examined for use in such physical property correlations. It would appear that these two ultrasonic properties offer the best possibilities of any of the ultrasonic properties used in this investigation.

ABSTRACT

Robert Wayne Crisp, Master of Science, 1971

Major: Civil Engineering

Title of Thesis: The Influence of Variation in Grain Size and Minimal Variation in Rock Type on the Quality of Rock Property Correlations for Intact Igneous Rocks

Directed by: Dr. Robert M. Scholtes, Head, Department of Civil Engineering

Pages in Thesis: 116. Words in Abstract: 274

Correlations of physical properties of rock and predictions of one property from a previously determined value of another property should be of tremendous value in the field of civil engineering. In particular, such correlations and rock property predictions would expedite multiple site evaluation and selection programs, and possibly allow for reduction in the number of various tests required to determine the physical properties now deemed necessary for competent design and construction in rock media.

Previous rock property correlations have generally encompassed many rock types, the objective being to determine general relationships typical of all rock types. The data, however, have frequently exhibited such a great degree of scatter that subsequent correlations

were of questionable value. Thus, in an effort to eliminate some of the scatter typical of many previous rock property correlations, this investigation was conducted to determine the influence of variation in grain size and minimal variation in rock type on the quality of rock property correlations for intact igneous rock types.

Physical property tests were conducted on 79 cylinderical specimens of granite and tonalite representing 10 drill sites. Values of ultimate uniaxial compressive strength and static Young's modulus of elasticity (tangent) were correlated with values of ultrasonic compressional pulse velocity, ultrasonic shear pulse velocity, ultrasonic Young's modulus, ultrasonic shear modulus, ultrasonic bulk modulus, and ultrasonic Poisson's ratio for each of the four following groups of specimens:

Group 1: All tonalite specimens tested from the Sierra Nevada Batholith, California.

Group 2: All tonalite specimens tested.

Group 3: All granite specimens tested.

Group 4: All specimens tested.

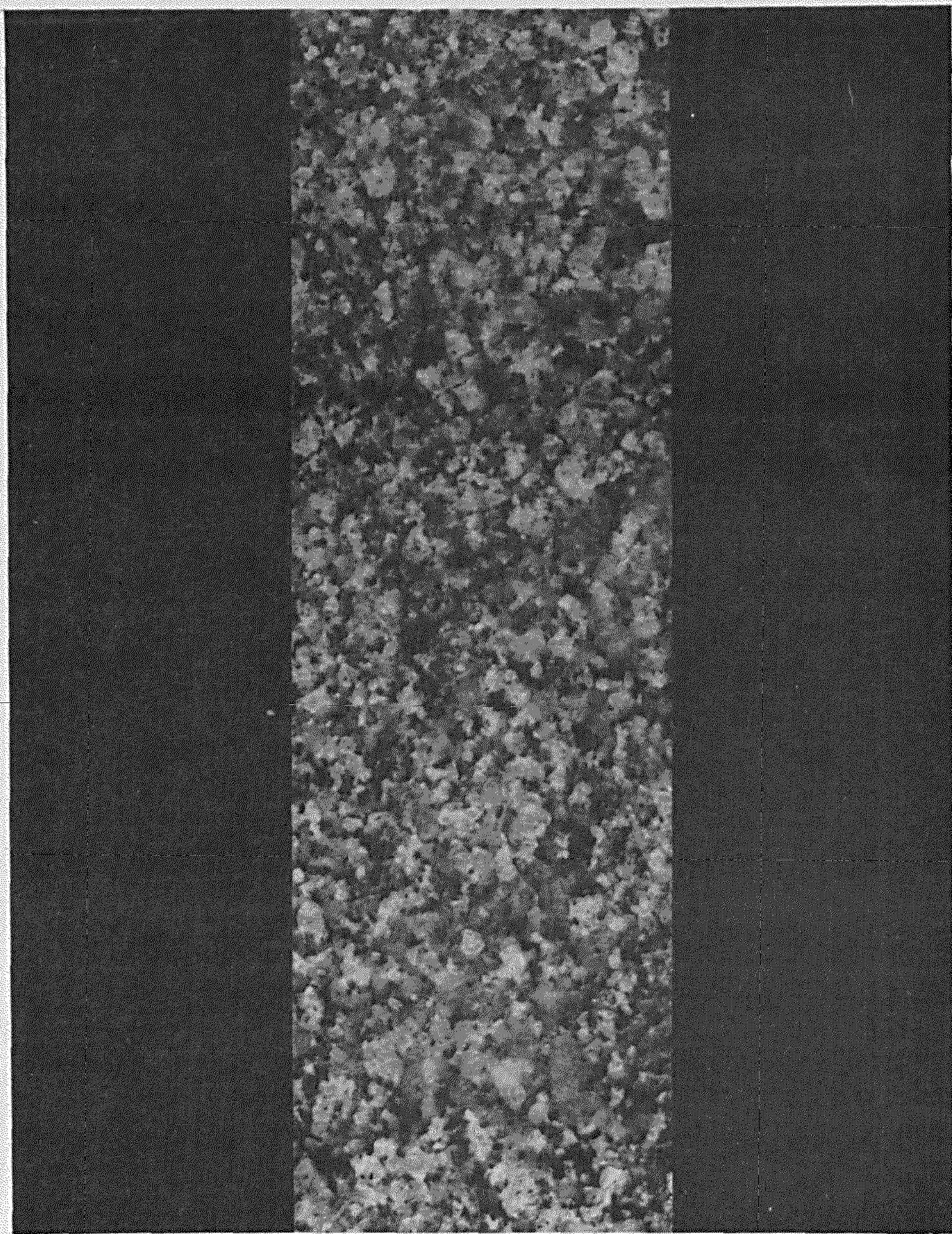
Comparison of the nature and quality of these linear correlations revealed that variation in grain size, as opposed to variation in mineral composition and geologic history as allowed within the confines of a particular rock type, appears to have primary influence on the degree of scatter typical of rock property correlations for a particular intact igneous rock type. Moreover, rock property correlations involving only one igneous rock type are generally superior to those involving several igneous rock types, the latter case frequently suffering from an overall lack of quality due to a larger degree of scatter brought about by the amalgamation of data relationships exhibiting different trends and different degrees of linear association.

APPENDIX I

PETROGRAPHIC DESCRIPTIONS

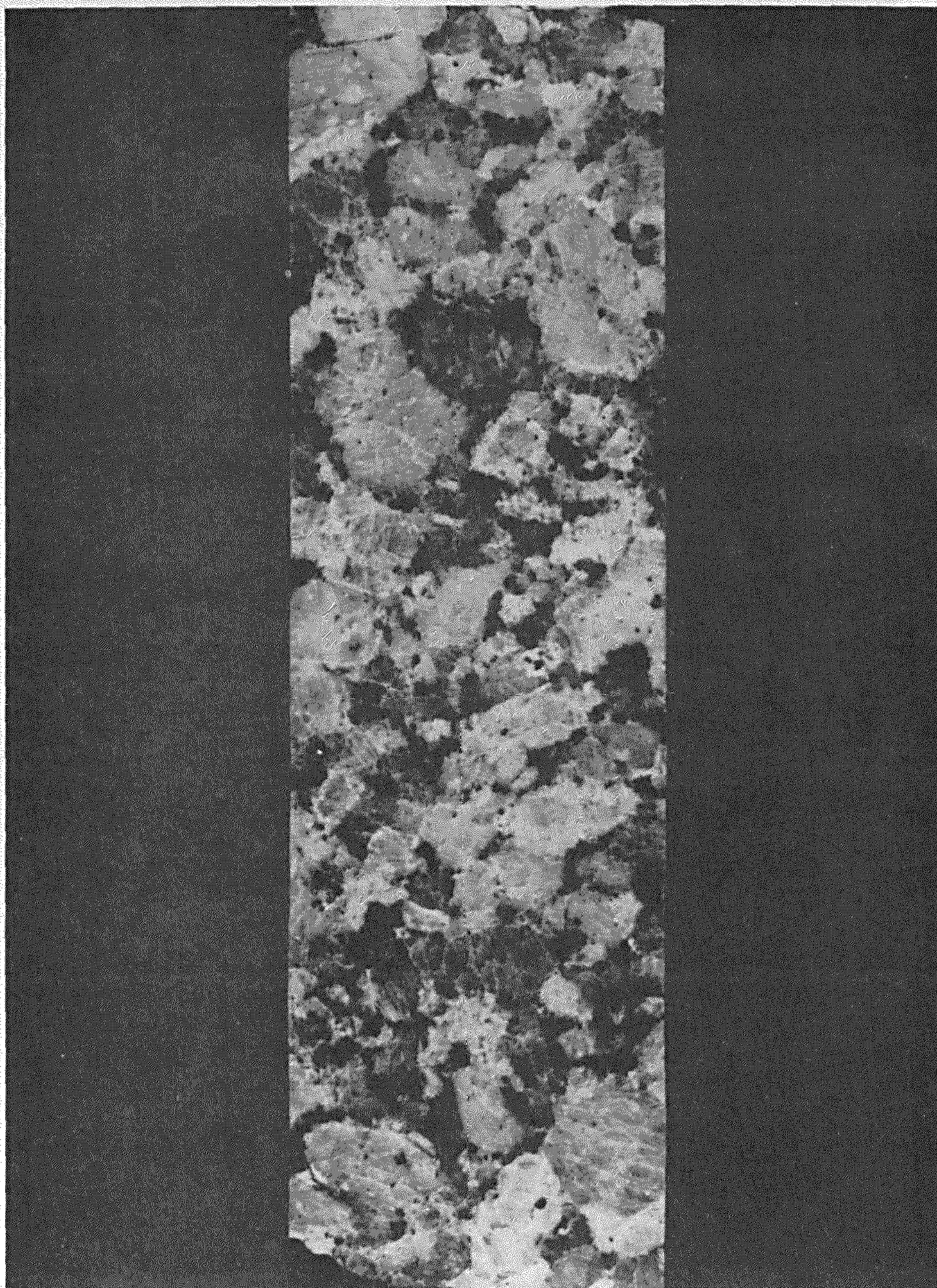
AND

POLISHED SECTION PHOTOGRAPHS

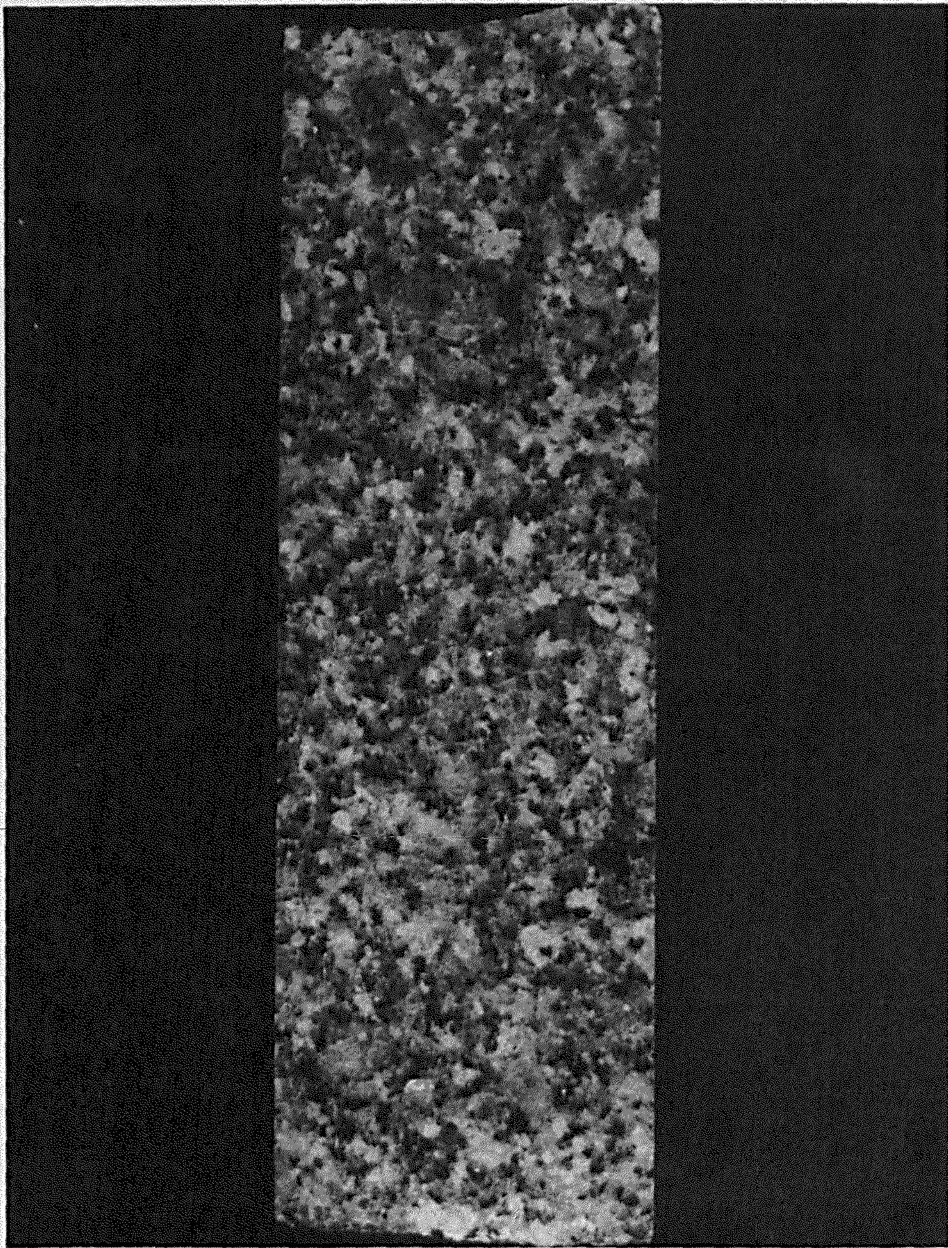


(a) Tonalite (Vermilion granite formation, Minnesota).

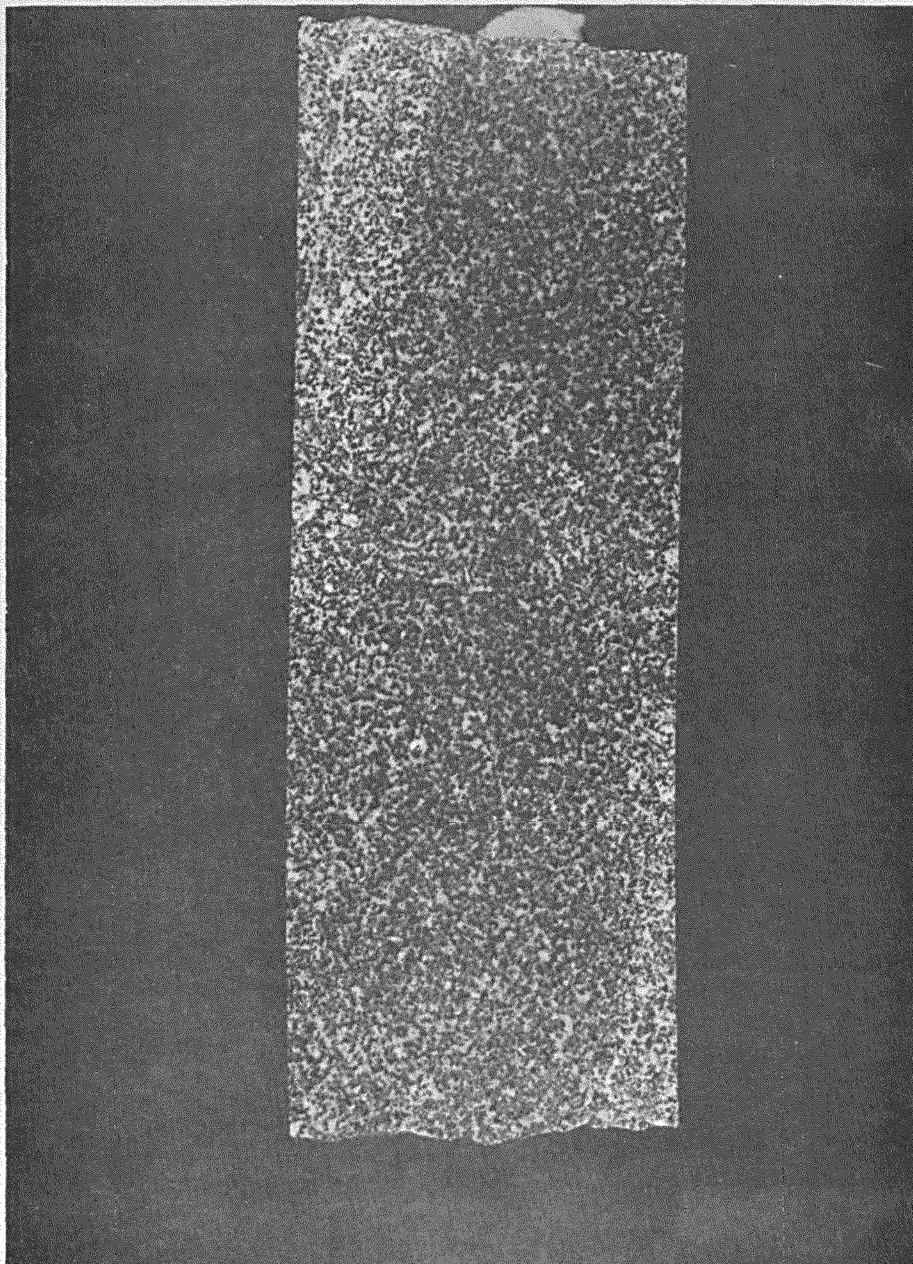
Brownish-gray medium- to coarse-gray tonalite. Biotite was broken and altered to chlorite. Microcline was unaltered and unbroken. Composed of 29% quartz, 48% plagioclase feldspar, 18% potassium feldspar (microcline), and 2% biotite with traces of magnitite, apatite, sphene, zircon, and calcite. Very few microfractures were detected.



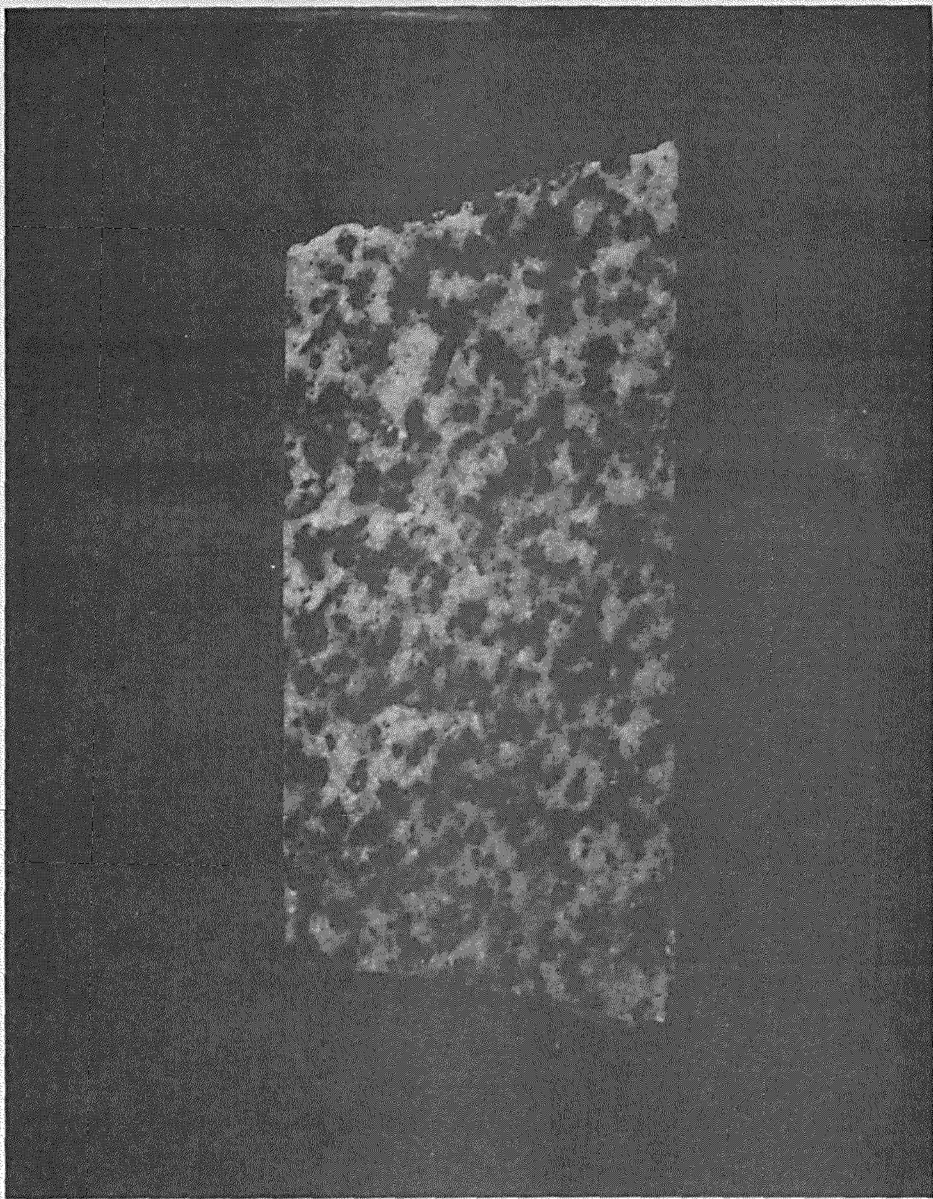
(b) Granite (Lucerne Pluton, Maine). Black and white, coarse-grained granite. Porphyritic texture. Specimens were unweathered and contained very few microfractures. Contained 28% quartz, 30% plagioclase feldspar, 30% potassium feldspar (microcline), and 11% biotite with traces of magnitite, apatite, chlorite, epidote, and hematite. Plagioclase was slightly altered to sericite.



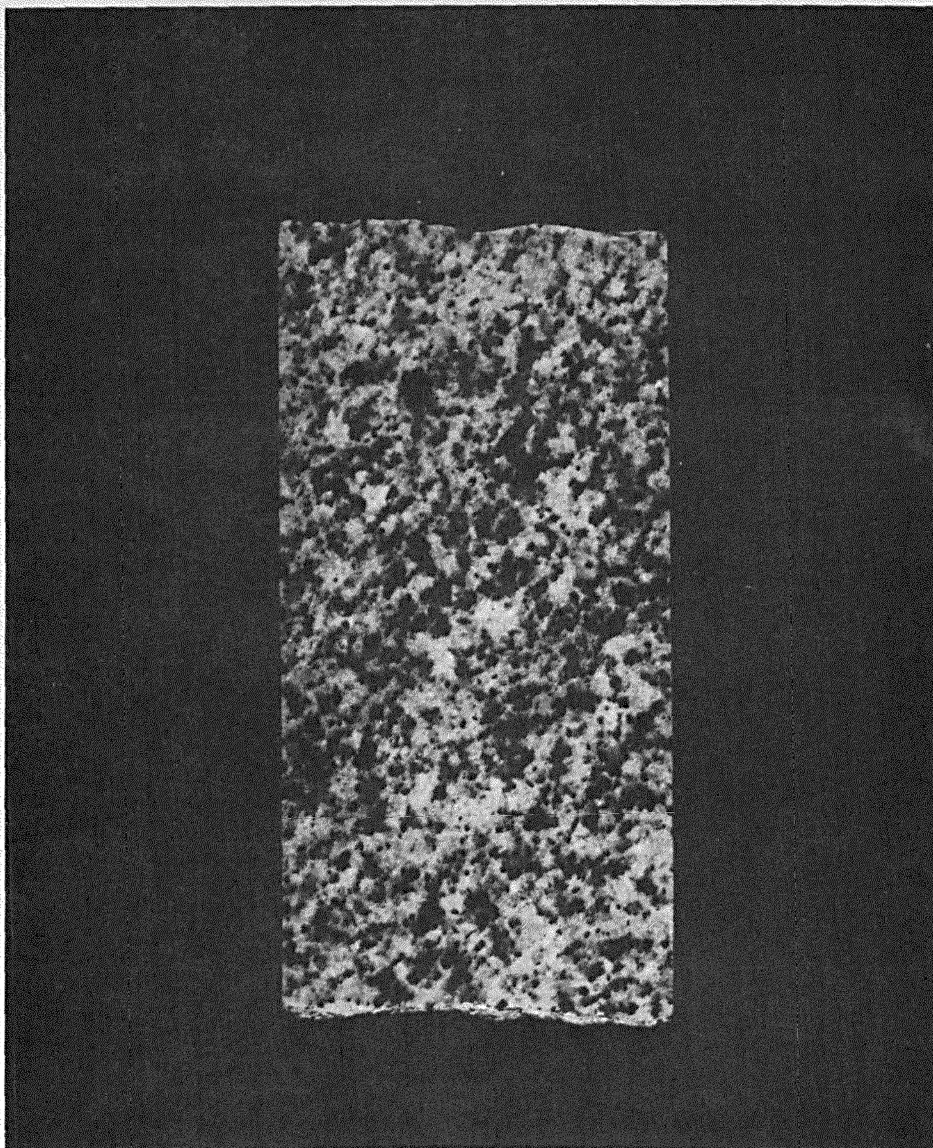
(c) Granite (Granite Mountains Uplift, Wyoming). Unweathered brownish-gray, coarse-grained granite. Microfractures were somewhat common. Contained 30% quartz, 30% plagioclase feldspar, 33% potassium feldspar (microcline), 5% biotite, 1% chlorite, and 1% magnetite and traces of epidote, apatite, and zircon. Anorthite content of the plagioclase was 15%. Plagioclase was slightly altered to sericite. Biotite was slightly altered to chlorite.



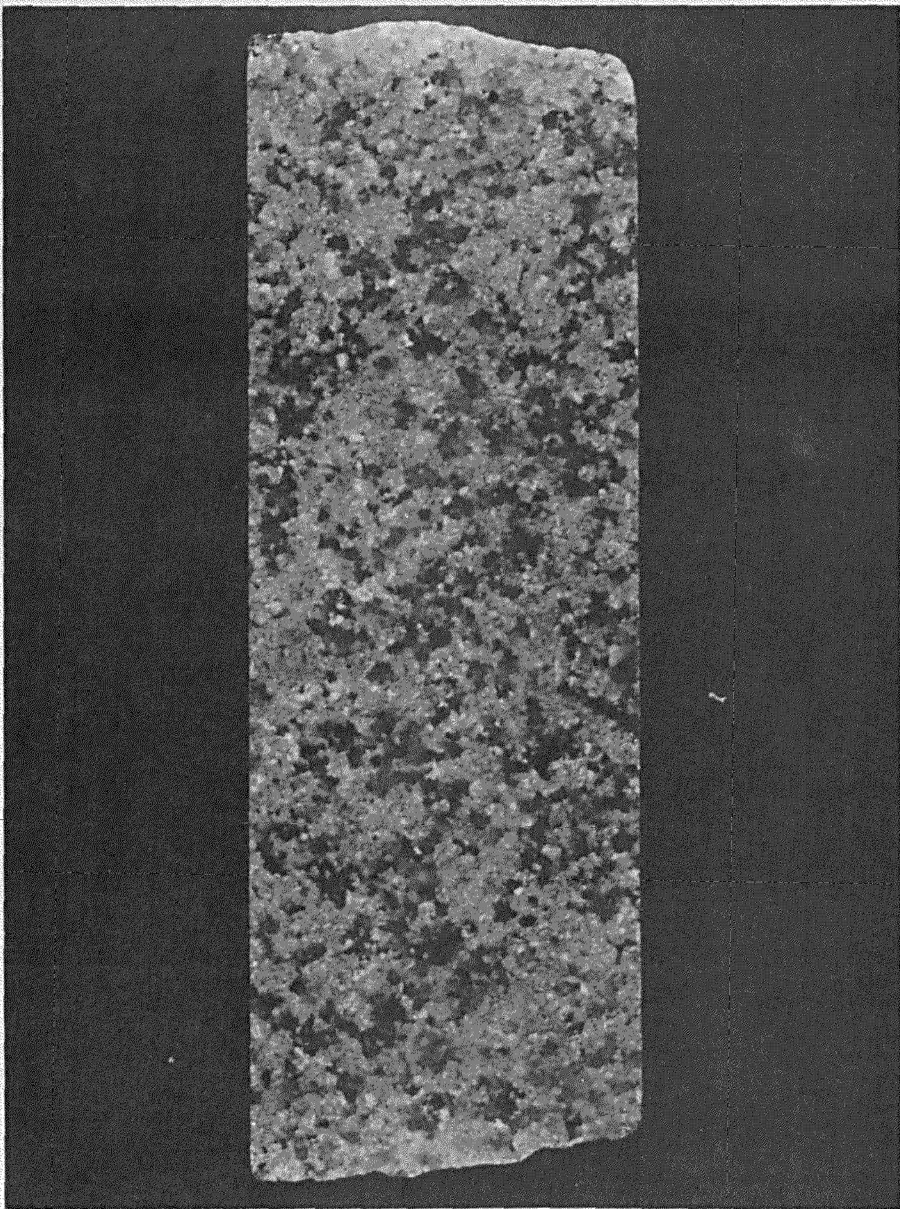
(d) Tonalite (Sierra Nevada Batholith, California). Fine-grained, dark colored rock. Sections were fresh and contained no macrofractures. Contained 18% quartz, 42% plagioclase feldspar, 19% hornblende, 16% biotite, 4% chlorite and traces of microcline and other accessary minerals. The biotite was slightly altered to chlorite.



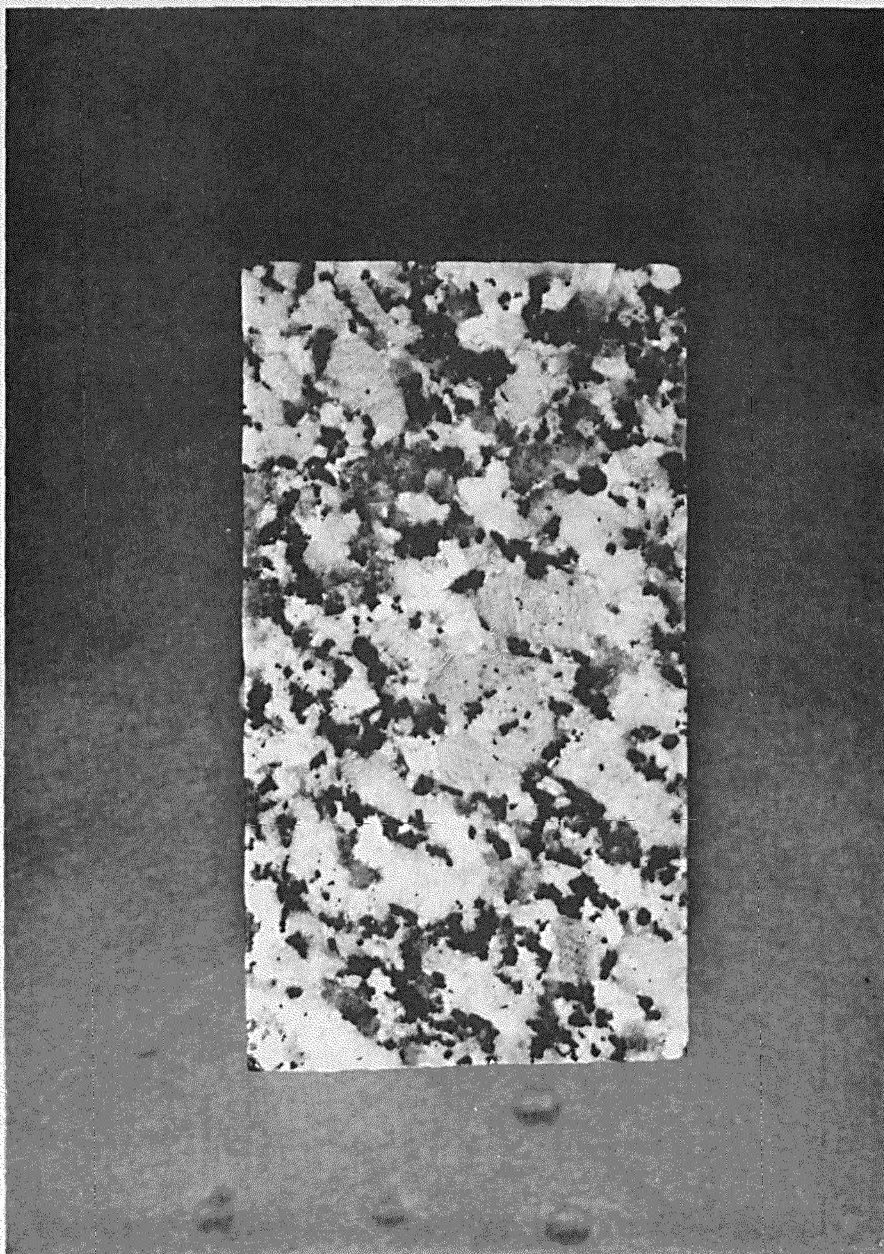
(e) Tonalite (Sierra Nevada Batholith, California). Medium- to coarse-grained, black and white tonalite. Sections were fresh and intact. Percentage mineral compositions were 21% quartz, 45% plagioclase feldspar, 13% hornblende, 20% biotite, and 1% chlorite. Traces of microcline were also detected. The biotite was slightly altered to chlorite.



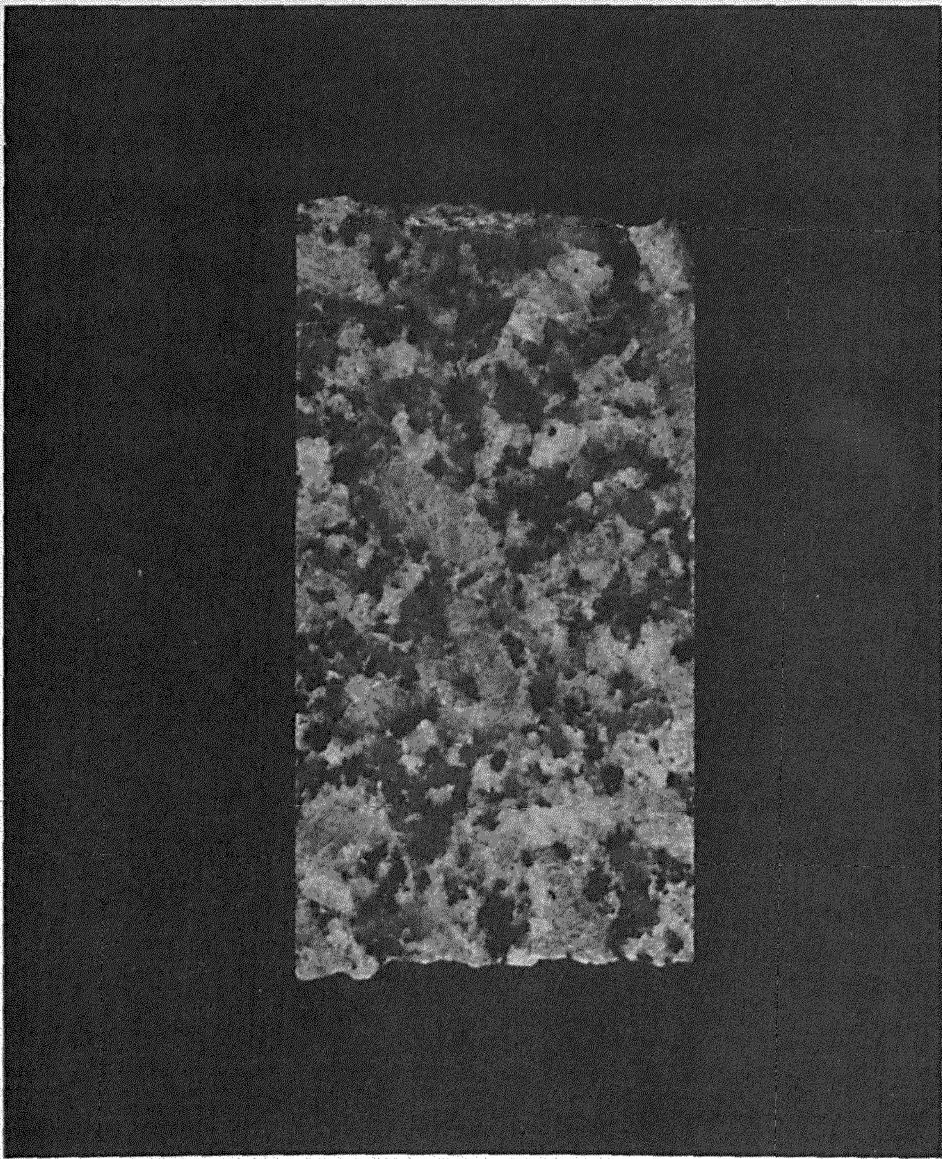
(f) Tonalite (Sierra Nevada Batholith, California). Medium-grained, black and white tonalite; much finer grained than the medium- to coarse-grained tonalite (e). Sections were unweathered. Percentage mineral compositions were 19% quartz, 46% plagioclase feldspar, 2% microcline, 12% hornblende, and 21% biotite. Traces of chlorite and magnetite were also detected. The biotite had been slightly altered to chlorite. No macrofractures were detected.



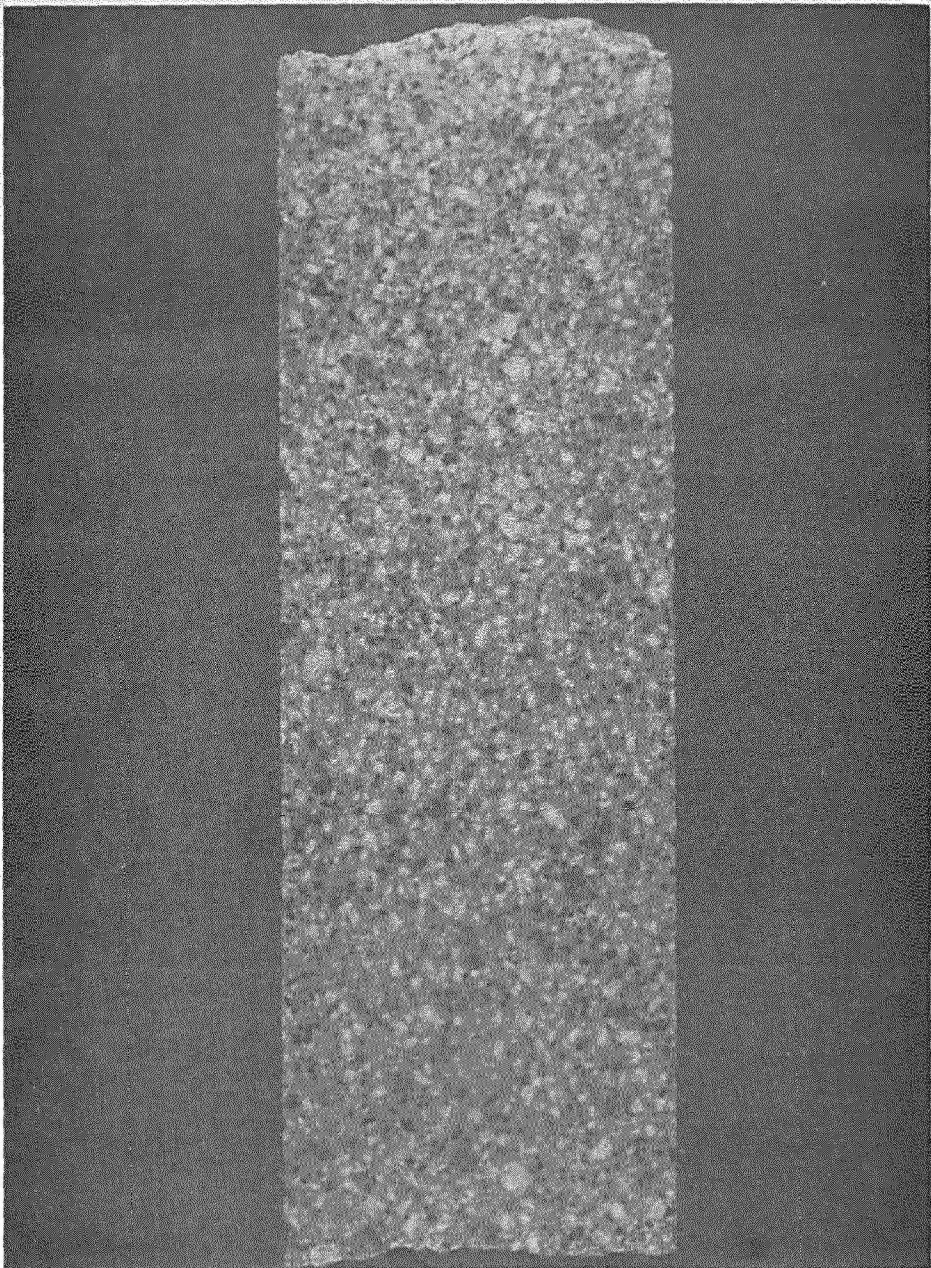
(g) Granite (Northwest of Lone Grove Pluton and Enchanted Rock Batholith, Texas). Medium-grained, red granite. Sections were intact and unweathered. More muscovite mica present than biotite mica. Percentage mineral composition is 30% quarts, 28% plagioclase feldspar, 33% potassium feldspar (microcline), and 9% biotite with traces of hornblende and chlorite.



(h) Granite (Sherman Granite Facies of Southern Laramie Range). Light-gray, coarse-grained granite. Composed of 24% quartz, 30% plagioclase feldspar, 32% potassium feldspar (microcline), 10% biotite, 4% hornblende, and a trace of chlorite. No preexisting fracture surfaces could be detected.



(i) Granite (Southern Laramie Range, Wyoming). Medium- to coarse-grained, pink granite, porphyritic texture. Percentage mineral composition is 29% quartz, 30% plagioclase feldspar, 34% potassium feldspar (microcline), 5% biotite, 1% hornblende, and 1% chlorite. Sections were unweathered and macroscopically free of fractures.



(j) Tonalite (Cedar City Tonalite, Utah). Light-gray, medium-grained tonalite. Mineral composition is 20% quartz, 44% plagioclase feldspar, 3% potassium feldspar (microcline), 21% hornblende, 5% biotite, 6% magnetite with traces of chlorite and other accessary minerals. Biotite was slightly altered to chlorite. Specimens were unweathered and macroscopically free of fractures.

APPENDIX II

CRITICAL VALUES

OF

CORRELATION COEFFICIENTS

Critical Values (r_{cr}) of Correlation Coefficients

Statistical Sample Size (n)	Critical Value (r_{cr})
21	0.55
35	0.43
36	0.39
39	0.40
40	0.40
71	0.30
79	0.29

BIBLIOGRAPHY

1. Blair, B. E. Physical Properties of Mine Rock, Part III. United States Bureau of Mines, Report of Investigations, 5130, June 1955.

2. Chayes, Felix. Petrographic Modal Analysis, New York, John Wiley and Sons, Inc., 1956.

3. D'Andrea, D. V., et al. "Prediction of Compressive Strength From Other Rock Properties," Colorado School of Mines Quarterly, Vol. 59, No. 4 (October 1964), 623-640.

4. Deere, D. U., and R. P. Miller. Engineering Classification and Index Properties of Intact Rock. Air Force Weapons Laboratory Technical Report No. AFWL-TR-65-116, December 1966.

5. Fairhurst, C. "Laboratory Measurement of Some Physical Properties of Rock," Proceedings of the Fourth Symposium on Rock Mechanics, Pennsylvania State University Mineral Industries Experiment Station, Bulletin No. 76, April 1961.

6. Judd, W. R. Strain Distribution Around Underground Openings, Technical Report No. 2. Advanced Research Projects Agency, Department of Defense, December 1969.

7. Judd, W. R., and C. Huber. "Correlation of Rock Properties by Statistical Methods," International Symposium on Mining Research, 2 Vol., New York, Pergamon Press, 1962.

8. Obert, L., and W. I. Duvall. Rock Mechanics and the Design of Structures in Rock. New York, John Wiley and Sons, Inc., 1967.

9. Obert, L., et al. Standardized Tests for Determining the Physical Properties of Mine Rock. United States Bureau of Mines, Report of Investigations, 3891, August 1946.

10. Rinehart, J. S., et al. "Propagation Velocity of Longitudinal Waves in Rocks - Effect of State of Stress, Stress Level of the Wave, Water Content, Porosity, Temperature, Stratification, and Texture," Proceedings of the Fourth Symposium on Rock Mechanics, Pennsylvania State University Mineral Industries Experiment Station, Bulletin No. 76, April 1961.

11. Shand, S. J. Eruptive Rocks. New York, John Wiley and Sons, Inc., 1949.

12. U. S. Army Engineer Waterways Experiment Station, Handbook for Concrete and Cement, August 1949.

13. Williams, H., et al. Petrography. San Francisco, W. H. Freeman and Company, 1954.

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4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

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11. SUPPLEMENTARY NOTES Report was also submitted to Mississippi State University, State College, Miss., as thesis for degree of Master of Science in Civil Engineering	12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT Previous rock property correlations have generally encompassed many rock types, the objective being to determine general relationships typical of all rock types. The data, however, have frequently exhibited such a great degree of scatter that subsequent correlations were of questionable value. Thus, in an effort to eliminate some of the scatter typical of many previous rock property correlations, this investigation was conducted to determine the influence of variation in grain size and minimal variation in rock type on the quality of rock property correlations for intact igneous rock types. Physical property tests were conducted on 79 cylindrical specimens of granite and tonalite representing 10 drill sites. Values of ultimate uniaxial compressive strength and static Young's modulus of elasticity (tangent) were correlated with values of ultrasonic compressional pulse velocity, ultrasonic shear pulse velocity, ultrasonic Young's modulus, ultrasonic shear modulus, ultrasonic bulk modulus, and ultrasonic Poisson's ratio for each of the four following groups of specimens: (a) all tonalite specimens tested from the Sierra Nevada Batholith, Calif., (b) all tonalite specimens tested, (c) all granite specimens tested, and (d) all specimens tested. Comparison of the nature and quality of these linear correlations revealed that variation in grain size, as opposed to variation in mineral composition and geologic history as allowed within the confines of a particular rock type, appears to have primary influence on the degree of scatter typical of rock property correlations for a particular intact igneous rock type. Moreover, rock property correlations involving only one igneous rock type are generally superior to those involving several igneous rock types, the latter case frequently suffering from an overall lack of quality due to a larger degree of scatter brought about by the amalgamation of data relationships exhibiting different trends and different degrees of linear association.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Granite						
Igneous rocks						
Rock properties						
Rock tests						
Tonalite						

Unclassified
Security Classification