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INTERRELATION OF PHYSICAL PROPERTIES AND IN-PLACE STABILITY OF DACITE AND GRANITE TO LOCAL GEOLOGY

by

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ABSTRACT

Study of nonhomogeneous, anistropic dacite and granite at the Nevada Test Site showed that local geology was the major factor in changing their physical properties and stability. Fractures, weathering and hydrothermal alteration were the geologic agents contributing most to the changes. Least-squares regression analyses established significant interrelations among physical properties, stability and local geology.

INTRODUCTION

Purpose and scope of the investigation

Rock, in general, is not a homogeneous, isotropic, perfectly elastic medium. Minerals, rock fragments, matrix material, and the cement which constitute a rock each has varying properties making the whole nonhomogeneous. Density differences between grain-to-cement or crystal-to-matrix interfaces, preferred orientation of minerals, bedding, and microscopic cracks in crystals and grains make the rock anisotropic and nonelastic. A large rock mass, in addition, has joints, faults, shears, weathered and alteration zones which further detract from its being homogeneous and isotropic.

The location, design, and construction of foundations, dams, tunnels or any other engineering structure that is dependent upon rock require an understanding of how the rock will behave under stresses. The nonhomogeneous and anisotropic nature of rock, however, makes any predictions of rock behavior extremely difficult.

One approach to the problem of rock behavior is to study intact rock samples in the laboratory to determine their lithologic, chemical and physical characteristics, and then attempt to relate these characteristics to the physical properties of the rock sample. Some physical properties of rock in current use can be described by means of elastic properties, ultimate strength, density, and porosity. Basic definitions of elastic properties, in terms of mathematical equations relating selected measurable physical properties, have been developed for homogeneous and isotropic materials. Rocks found in nature rarely meet these ideal conditions, therefore, the assumption that equations of mechanical theory can be applied to rocks requires experimental justification (J. M. Ide, 1936).

A method for relating the physical properties of nonhomogeneous, anisotropic rhyodacite core samples, henceforth called dacite, to its lithologic, weathering, and alteration characteristics will be discussed. Interrelations of porosity, density, unconfined compressive strength and elasticity of the dacite will be presented in mathematical and graphically form. From these interrelations in dacite core samples it will be shown that reasonable predications of elastic and unconfined strength values can be made from easily obtained porosity measurements.

A second approach to understanding the behavior of rock under stressed conditions is to relate the effect local geology has on the stability and physical properties of a rock mass. Examination of four 650 foot NX cores taken from inclined holes drilled in quartz monzonite, henceforth referred to as granite, permitted detailed logging of lithology, faults, joints, and the relative degree of weathering and hardness of the granite. A 70-foot hemispherical chamber, entry shaft, and communication drifts constructed in the granite allowed detailed geologic mapping of the in-place rock and recording of construction and stability conditions. The drill holes penetrated the underground complex, making it possible to relate underground conditions to the detailed core logs. It will be shown by means of mathematical equations, graphs and a Rock Quality Table that physical properties and construction and stability conditions in granite are directly related to joint and fault intensity and to the degree of weathering and hardness of the rock. The effects of local geology as seen in cores can, therefore, be used to make reasonable predictions of the physical properties and construction conditions of granitic rock.

Acknowledgements

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This thesis is based on geologic investigations of two Department of Defense projects at the Nevada Test Site to which I was assigned as a member of the Special Projects Branch of the U.S. Geological Survey. The field work and compilation of data were accomplished over a period of time between 1962 and 1966. All mapping, core logging, interpretations and statistical analyses were done by the author, unless otherwise noted. Conclusions presented in this discussion are the result of observations made during surface and underground mapping, core logging, petrographic examination, and analyses of laboratory data from core and rock samples. Application of principles derived from this investigation are now being routinely used in all geologic investigations performed by the U.S. Geological Survey of underground construction projects at the Nevada Test

Site. The author also employed core logging techniques developed from these studies for exploration and engineering geology investigations in the Piceance Creek Basin of western Colorado on behalf of the Atomic Energy Commission's Plowshare nuclear in situ oil shale experiments.

Fundamental principles of rock mechanics

Mechanics is defined as "the science that deals with the action of forces on bodies and with motion, comprised of kinetics, statics and kinematics" (Random House Dictionary, 1966). Rock mechanics is, therefore, the study of forces acting on rock. In order to establish a background for discussion of rock physical properties in relation to the geologic history of a region, a brief review of some fundamental principles of mechanics follows.

Elasticity is that property of a substance which allows the substance to resist deformation when subjected to the action of an external force (L. L. Nettleton, 1940, p. 231-244). The elastic properties of a substance can be measured in terms of stress and strain. Stress is defined as the ratio of the internal force (F), which is brought into play when a substance is distorted in any way, to the area (A) over which this force acts. Thus

$$\text{Stress} = \frac{F}{A} \qquad (1)$$

Strain is defined as the ratio of change in size or shape of a body to original size or shape, and has no dimensional units.

The relationship between stress and strain is expressed by Hooke's law which states that, for an elastic body the ratio of the stress to the strain produced is a constant, or

$$\frac{\text{Stress}}{\text{Strain}} = k \qquad (2)$$

The modulus of elasticity is called k.

Young's modulus (E) is a measure of the stress-strain ratio of a substance that is under simple tension or compression. It defines the strain in terms of the change in length of a body from its original length when a simple tensional or compressional stress is applied, or

$$\text{Strain} = \frac{\text{change in length}}{\text{original length}} = \frac{\Delta L}{L} \qquad (3)$$

Thus from Hooke's law (equation 2) Young's modulus (E) can be defined as

$$E = \frac{F/A}{\Delta L/L} \qquad (4)$$

Shear modulus (μ) is a measure of the stress-strain ratio for simple shear. It can be described as a measure of resistance to change of shape without change of volume; a pile of cards might be sheared by sliding each one successively a slight distance over the next. The shearing strain is expressed as the ratio of lateral displacement (ΔL) of a body between two points lying in parallel planes in the line of force, to the vertical distance (L) between the planes perpendicular to the line of force.

$$\mu = \frac{F/A}{\Delta L/L} \qquad (5)$$

Poisson's ratio (σ) is a measure of a geometric change of stress-strain relation and, therefore, has no units. In the case of a cylindrical body under compression, the original length (L) is compressed elastically to a length $L - \Delta L$. Its original diameter (D) then increases to $D + \Delta D$. If the cylinder is under tension the changes are of the same magnitude but opposite in sign. This change of shape is expressed as the ratio of the fractional change in diameter ($\Delta D/D$) to the fractional change in length ($\Delta L/L$), or

$$\sigma = \frac{\Delta D/D}{\Delta L/L} \qquad (6)$$

Theoretically Poisson's ratio cannot have a value greater than 1/2.

Bulk modulus (β) is a measure of the stress-strain ratio under simple hydrostatic pressure and represents a volumetric change. It can be expressed as

$$\beta = \frac{F/A}{\Delta V/V} \qquad (7)$$

where $\Delta V/V$ is the change in volume per unit volume.

A linear, homogeneous, isotropic, and elastic medium can transmit two types of waves which have different speeds of propagation, depending on the elastic constants. The two types of waves are defined as compressional (longitudinal, P) waves, and shear (transverse, S) waves. The compressional waves are the motions of particles in the medium parallel to the direction of propagation. The shear waves are the motions of particles in the medium perpendicular to the direction of propagation (L. L. Nettleton, 1940). The relation between the waves and the four elastic constants (J. M. Ide, 1936) are:

$$V_c^2 = \frac{E}{\rho}\,\frac{1-\sigma}{(1-\sigma)(1-2\sigma)} = \frac{\mu}{\rho}\,\frac{4-E/\mu}{3-E/\mu} = \frac{3}{\rho\beta}\,\frac{3+E\beta}{9+E\beta}$$

$$V_s^2 = \frac{E}{\rho}\,\frac{1}{2(1+\sigma)} = \frac{\mu}{\rho} = \frac{E}{\rho}\,\frac{3}{9-E\beta}$$

The elastic constants can also be related to each other by the following equations:

$$E/\beta = 3(1-2\sigma) \quad (10)$$

$$E/\mu = 2(1+\sigma) \quad (11)$$

$$E/\beta + 3E/\mu = 9 \quad (12)$$

$$\frac{\mu/\beta}{3} = \frac{1-2\sigma}{2(1+\sigma)} \quad (13)$$

where E is Young's modulus

β is bulk modulus

μ is shear modulus

σ is Poisson's ratio

ρ is the density of the medium

V_c is the compressional velocity in the medium

V_s is the shear velocity in the medium.

Strength is the limiting stress that a solid can withstand without failing by rupture or continuous plastic flow. Rupture strength or breaking strength refers to the stress at the time of rupture (Billings, 1954, p. 17). Ultimate strength is the greatest stress that a substance can stand under normal short-time experiments; that is, the highest point on a stress-strain diagram (Billings, 1954, p. 16). Compressive strength is the load per unit area under which a block fails by shear or splitting (Terzaghi, 1950). Fundamental strength is the maximum stress that a substance can withstand, regardless of time, under given physical conditions without rupturing or plastically deforming continuously (Billings, 1954, p. 24).

INTERRELATION OF DACITE PHYSICAL PROPERTIES TO LOCAL GEOLOGY

Introduction

One phase of the Department of Defense nuclear ram jet project, code named Pluto, called for an experimental high pressure underground air storage chamber. Basically the plan required a pilot chamber to be constructed in rock that would provide support for a thin steel liner that would hold the pressurized air. The concept can be compared to an inflated automobile innertube encased and supported by an outer tire. The chamber design demanded that the rock be able to restrain pressures up to 3,000 psi.

The site chosen by the Department of Defense, based mainly on logistical support requirements, is in Wahmonie Flat located on the Nevada Test Site (fig. 1). The Nevada Test Site lies in southeastern Nye County approximately 70 miles northwest of Las Vegas, Nevada.

Geology of Wahmonie Flat

Extrusive rocks. The extrusive rocks in the area make up part of the Wahmonie Formation of late Miocene and early Pliocene(?) age (Poole and others, 1965). The Wahmonie Formation at the construction site consists of dacitic lava flows and their associated breccias (fig. 2). The flows in general are composed of stony interiors enveloped by porphyritic glass zones, which in turn are enclosed by rinds of black or gray glass. The associated breccias are made up of fragments of lava enclosed in a fine matrix of cinders, rock fragments, and glass. The breccias are more susceptible to weathering than are the more dense flow rocks.

The rocks of Wahmonie Flat are chemically similar, although the oldest flows are slightly more silicic than the youngest. Phenocrysts of plagioclase, biotite, hornblende, hypersthene, quartz, and finely disseminated

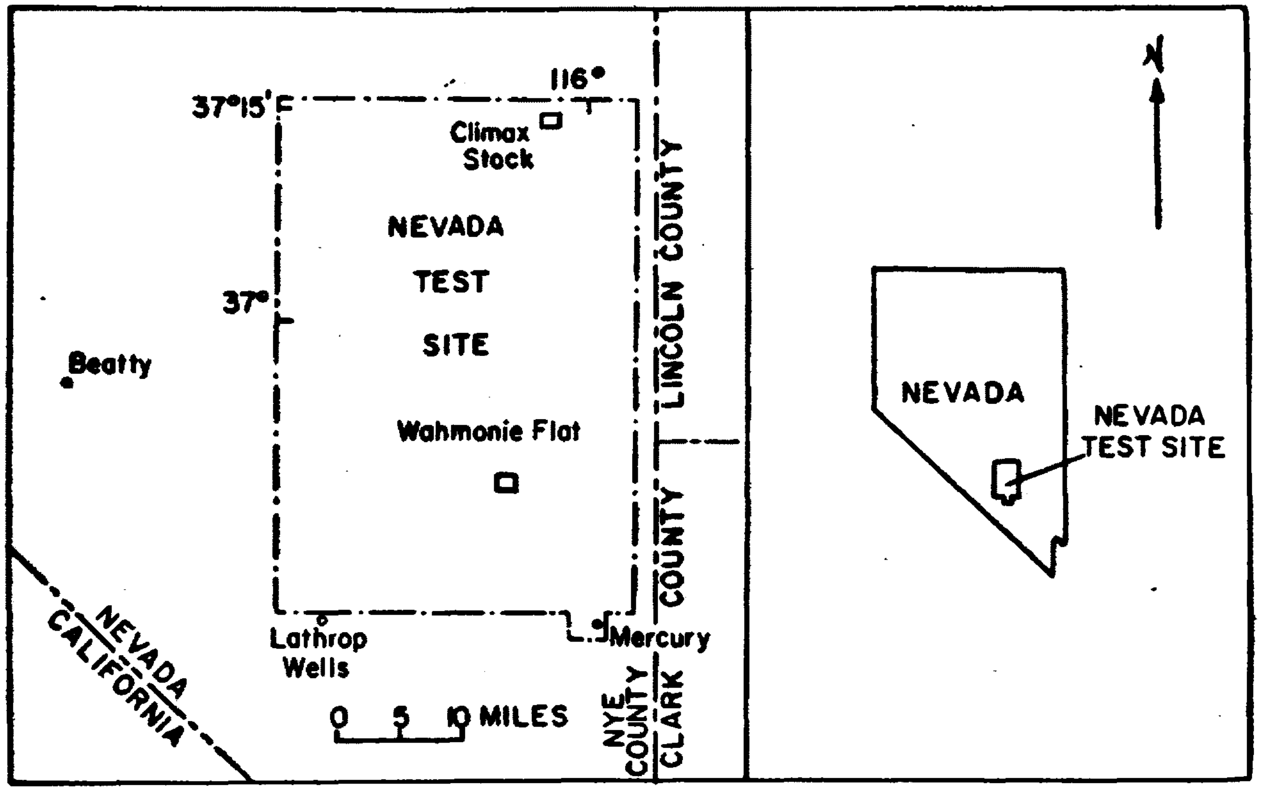


Figure 1.--Location map showing Wahmonie Flat and Climax stock, Nye County, Nevada.

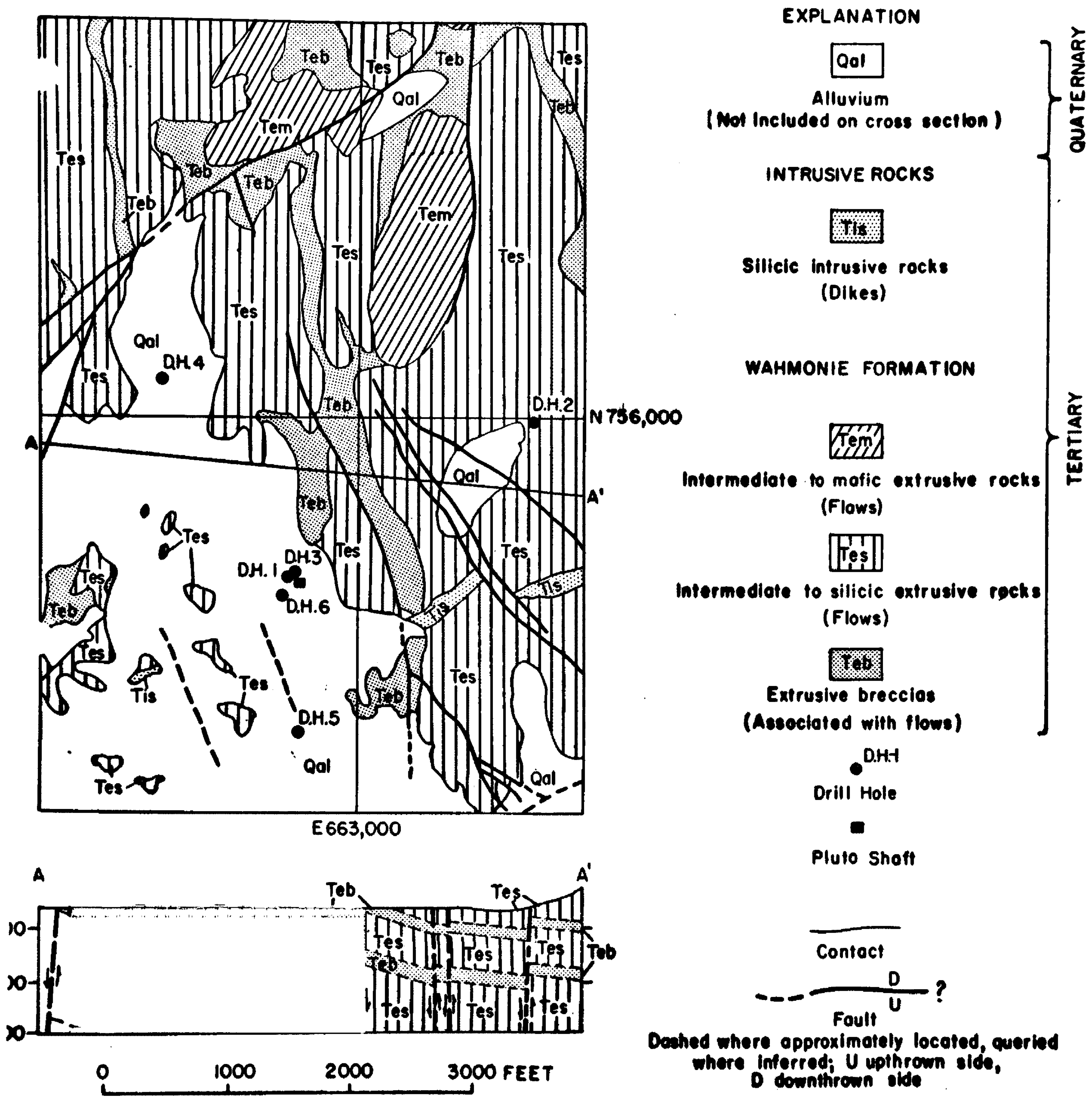


Figure 2.--Geologic map of Wahmonie Flat, Nye County, Nevada, showing Pluto shaft and drill hole.

magnetite embedded in a glassy or stony groundmass, give the rock a porphyritic texture. The Pluto underground chamber is constructed in one of the dacite flows.

In places the lavas have been altered by hydrothermal solutions and have been impregnated with cryptocrystalline quartz. Hydrothermal alteration is extensive along shear zones. Extensive weathering of the rock has occurred near the surface and along joint planes in both the altered and unaltered rocks. The groundmass has been especially affected by the weathering process, causing increased porosity and generally weakening of the rock.

Structure. Structural features include normal faults, shear zones, and joints. Tectonic activity, occurring during late Tertiary times throughout Nevada and most of southwestern United States, resulted in regional uplift and major block faulting. Much of the structure is related to these great earth movements. The high-angle normal faults in the area generally strike either northeast or northwest. Vertical displacement along the faults in the area does not exceed 100 feet, although there is evidence of considerable lateral displacement. The faulted blocks are tilted to the east. North- and northeast-trending shear zones, dipping from about 45 degrees to vertical, occur in both the altered and unaltered rocks. The greatest amount of hydrothermal alteration has taken place along these zones.

Ground water. Garber and Thordarson (1962, p. 1) state that the piezometric surface of the regional water table in Yucca Flat which is located about 5 miles east of Wahmonie Flat, is approximately 2,400 feet above sea level. Soundings taken in six drill holes at the Pluto site (fig. 2), however, indicated that an extensive perched body of water exists in the area. The average elevation of the perched zone was 3,935 feet above sea level which is some 1,500 feet above the regional water table. The perched water body, encountered during shafting, occurred at a depth of 158 feet below ground surface or at an elevation of 3,933 feet. Color changes in the drill cores and the presence of iron-oxide coatings along joint planes suggest the perched zone may extend to 300 feet below ground surface or to about 3,790 feet in elevation.

Dacite physical properties and local geology

Examination of cores from three exploratory borings at the Pluto chamber site showed that the dacite, down to a depth of 1,000 feet from ground surface, could be divided into one unaltered sub zone designated as Zone Ia and four distinctive weathered and alteration zones referred to as Zones I, II, III and IV (fig. 3). These zones provided an excellent opportunity to study the effects that the geologic history of the region had on the dacite. Detailed surface and underground mapping, core logging (Table 1), chemical and x-ray analyses (Tables 2 and 3), physical properties tests (Table 4) and petrographic examination (Table 5) provided the pertinent information for the effects studies. Each zone will be discussed under topical headings of the rock's physical and chemical characteristics. Testing of samples for physical properties follows American Society for Testing Materials standards (ASTM, 1952).

<u>Hand specimens</u>. The core from Zone I (Table 1 and fig. 3) is very light gray to light bluish gray, severely to moderately weathered, porous and generally weak. The severely weathered core, bleached to a very light gray and white, slacks readily in water. Within Zone I, generally below 100 feet in depth, occasional lenses or blocks of unaltered and unweathered

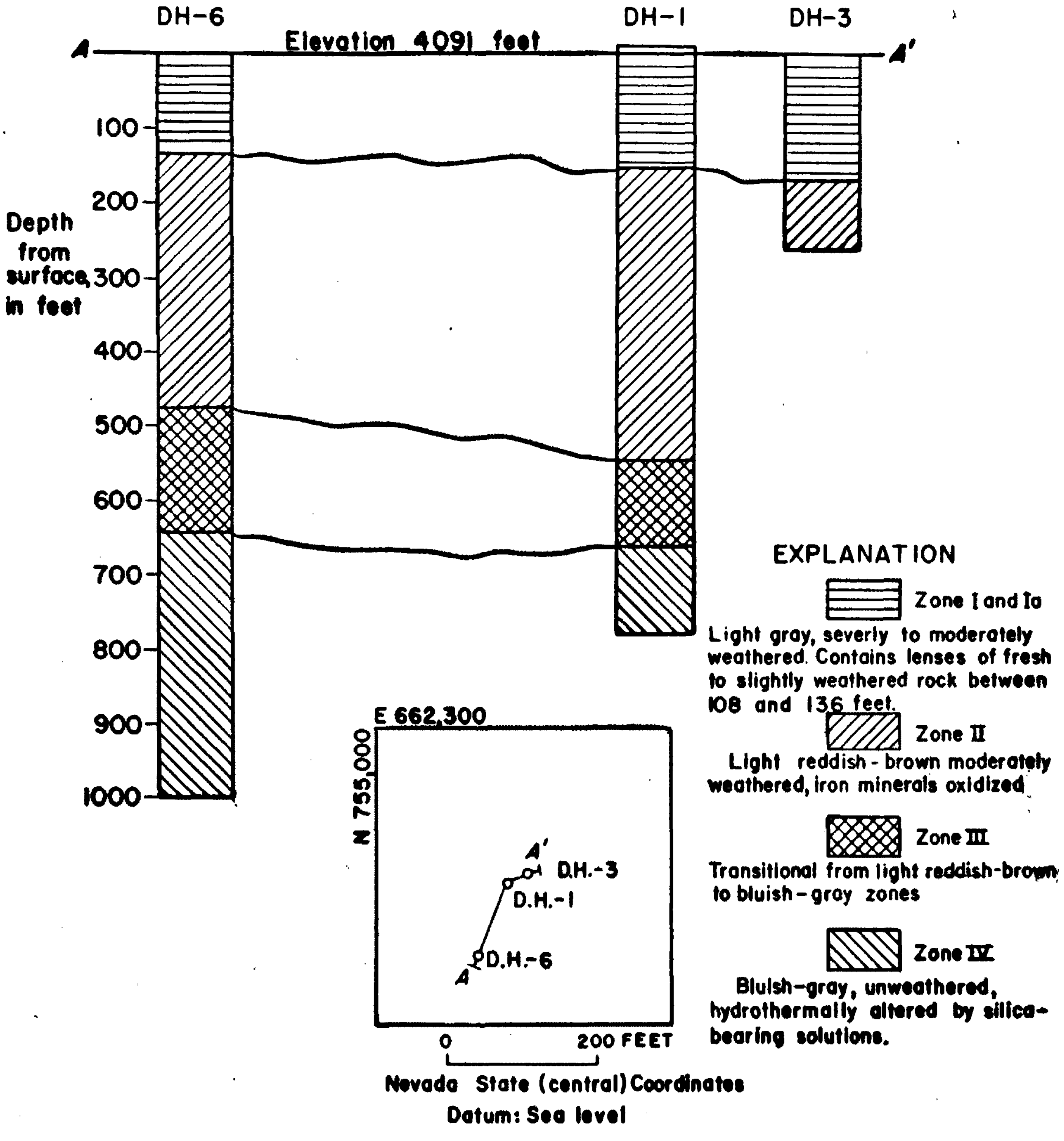


Figure 3.--Cross section showing weathered and hydrothermally altered zones in dacite flow. Determined from Drill Holes 1, 3, and 6, Wahmonie Flat, Nye County, Nevada.

Table 2.--Chemical analyses of dacite core samples from Wahmonie Flat, Nye County, Nevada

[Analysts: P. L. D. Elmore, I. J. Barlow, S. D. Botts, and G. W. Chloe.
Location of drill holes by Nevada State (central) coordinates:
D.H.-1, N. 754,788, E. 662,481; D.H.-2, N. 755,967, E. 664,321;
D.H.-3, N. 754,808, E. 662,507.]

Sample number---	D.H.-1A	D.H.-1B	D.H.-1D	D.H.-1F	D.H.-1K	D.H.-1S	D.H.-1U	D.H.-1X	D.H.-2D	D.H.-2F	D.H.-3H
Depth in feet--	65.5	83.3	109.8	130.0	217.5	400.0	450.0	550.0	83.5	108.0	221.0
SiO_2	64.0	64.9	64.5	62.6	63.5	63.4	64.4	63.8	61.7	61.4	62.6
Al_2O_3	15.9	13.8	16.2	16.2	16.6	15.4	15.7	16.2	16.7	17.2	15.7
Fe_2O_3	2.4	3.0	2.4	3.1	3.3	3.8	4.1	4.3	5.2	5.3	4.7
FeO	1.1	.16	1.1	.27	.30	.11	.06	.18	.09	.13	.10
MgO	1.8	1.9	1.4	1.8	1.2	1.6	1.3	1.2	1.6	1.4	1.4
CaO	3.8	4.7	3.7	4.4	4.2	3.9	3.2	3.0	4.1	4.6	3.8
Na_2O	2.3	1.6	2.6	2.2	2.7	2.6	2.6	2.6	2.8	3.0	2.3
K_2O	3.1	1.1	3.7	1.2	3.4	3.6	3.6	3.6	2.8	2.6	3.8
H_2O	4.8	6.9	3.6	6.7	3.1	3.3	3.5	3.8	3.7	3.2	4.0
TiO_2	.50	.47	.48	.50	.52	.54	.57	.58	.68	.70	.52
P_2O_5	.28	.20	.24	.27	.26	.23	.24	.24	.30	.32	.24
MnO	.09	.05	.08	.02	.05	.09	.05	.03	.05	.05	.08
CO_2	<.05	1.2	<.05	.15	.62	1.6	.51	.10	<.05	<.05	.88
Sum---- (percent)	100	100	100	99	100	100	100	100	100	100	100

Table 3.--X-ray analyses of core samples from drill holes D.H.-1, D.H.-2, D.H.-3, D.H.-4, and D.H.-5, Wahmonie Flat, Nye County, Nevada

[Analyst: Theodore Botinelly]

Sample No.	Depth (feet)	Cristobalite 1/	Clay	Mica	Feldspar	Dolomite	Calcite
D.H.-1B	83.3	4	3	4	4	-	-
D.H.-1F	130.0	4	3	4	2-3	-	-
D.H.-1U	450.0	2-3	3	5	4	-	-
D.H.-1X	550.0	2-3	3	-	3	-	-
D.H.-2D	83.5	3	3	-	2-3	-	-
D.H.-2F	108.0	3	3	-	3	-	-
D.H.-3H	221.0	3	4	5	4	-	-
D.H.-4F	99.0	3	4	-	3	-	-
D.H.-4T	252.5	3	4	-	2-3	-	-
D.H.-5A	13.0	3	4	-	4	-	-
D.H.-5B	35.5	3	3	-	4	-	5
D.H.-5D	75.5	2-3	4	-	4	-	-
D.H.-5L	224.5	5	4	5	3	5	5
D.H.-5R	311.0	3	3	-	4	-	-

1/ Code

1 = >75 percent
2 = 50-75 percent
3 = 25-50 percent
4 = 10-25 percent
5 = <10 percent

Location of drill holes by Nevada State (central) coordinates

D.H.-1	N. 754,788, E. 662,481
D.H.-2	N. 755,967, E. 664,321
D.H.-3	N. 754,808, E. 662,507
D.H.-4	N. 756,262, E. 661,491
D.H.-5	N. 753,602, E. 662,558

Average physical property values of dacite core samples calculated for alteration zones I, Ia, II, III and IV, Wahmomie Flat, Nye County, Nevada

Alteration Zone	Description of Zone	Approx. depth (feet)	Average porosity (percent)	Grain density (g/cc)	Dry bulk density (g/cc)	Saturated bulk density (g/cc)	Dynamic					Static			Magnetic susceptibility (10^{-6}cgs)
							Young's Modulus (10^6psi)	Poisson's ratio	Shear Modulus (10^6psi)	Longitudinal velocity (fps)	Transverse velocity (fps)	Young's Modulus (10^6psi)	Poisson's ratio	Unconfined compressive strength (10^6psi)	
I	Light gray, severely to moderately weathered.	160	18.6 (30)1/	2.52 (30)	2.02 (35)	2.27 (7)	2.36 (6)	0.16 (8)	0.94 (8)	8,929 (8)	5,693 (8)	1.74 (3)	0.22 (2)	9,200 (3)	1,325 (22)
Ia	Lenses and blocks contained within zone I, fresh to slightly weathered.		6.2 (6)1/	2.51 (6)	2.36 (6)	2.41 (3)	6.71 (4)	0.23 (4)	2.74 (4)	15,109 (3)	8,563 (3)	---	---	---	1,768 (5)
II	Light reddish-brown, moderately weathered, oxidized iron minerals.	475	10.8 (83)1/	2.54 (83)	2.27 (82)	2.36 (11)	4.03 (32)	0.15 (32)	1.75 (32)	11,742 (32)	6,595 (32)	3.44 (16)	.16 (15)	14,731 (16)	256 (47)
III	Transitional between zone II and IV, interbanded light reddish-brown and bluish-gray.	640	9.5 (17)1/	2.55 (17)	2.30 (17)	---	4.37 (2)	0.18 (2)	1.86 (2)	12,189 (2)	7,635 (2)	2.11 (5)	0.15 (2)	13,833 (3)	476 (13)
IV	Bluish-gray, unweathered, hydrothermally altered by silica bearing solutions.	+1,000	8.2 (16)1/	2.56 (16)	2.35 (16)	---	4.78 (2)	0.10 (2)	2.16 (2)	11,505 (2)	8,133 (2)	4.82 (4)	0.28 (2)	15,533 (3)	1,508 (6)

1/ Number in parenthesis is number of samples tested.

Table 5.--Petrographic modal analyses of 10 dacite porphyry core thin sections from D. H. 1 between depths 65-550 feet.

/Analyses are given in percentage of total volume of rock./

Mineral	Percent
Quartz	trace
Glass matrix	72.0
Plagioclase	19.5
Biotite	3.7
Hornblende	0.4
Hypersthene	0.1
Iron Oxides	1.9
Calcite	1.9

rock occur that are suggestive of fresh blocks of rock found below the saprolite zone in a soil profile. The core from this rock, designated as Zone Ia, is representative of the unweathered and unaltered dacite. Zone Ia core is light gray, hard, slightly weathered to unweathered, and has a partly devitrified glassy groundmass. Jointing is more pronounced in Zone Ia than in the severely weathered rock of Zone I due to its preservation in the more brittle rock. The core from Zone II is light reddish brown, oxidized, moderately to slightly weathered, unaltered to slightly hydrothermally altered, slightly porous, and of intermediate hardness to hard. The competency of the core improves below 370 feet in depth, as reflected by its generally harder and less porous character. Joints in the core are mostly open and coated with iron-stained clay and calcite above the 220-foot depth, but become tighter downward to about the 300-foot depth. Below 300 feet the joints are mostly sealed with iron-stained clay and calcite. The joint spacing above 370 feet averages 8 inches, and below 370 feet averages 2 feet. A detailed joint study of D.H. 6 core indicated, however, that the joint spacing gradually increased below the 285-foot depth, whereas the improved character of the core did not occur until 370 feet. A transitional zone, designated as Zone III, lies between 500 and 650 feet in depth. Alternating reddish brown and bluish gray sections of core, which are characteristic of both the overlying and underlying zones, mark a gradual change in the weathering and alteration of the rock. Zone IV, lying below 650 feet in depth, is bluish gray, hydrothermally altered, unweathered to slightly weathered along joint planes, nonoxidized, and hard. Joint spacing averages 2 feet. The majority of joints are sealed with unstained calcite, and the core occurs in long unbroken lengths. Locally, hydrothermal solutions have deposited opal and gypsum.

Thin sections. Petrographic examination of thin sections samples from each zone are summarized in Table 5. In Zone I weathering is seen to have attacked the perlitic groundmass, changing portions of it to clay minerals and obliterating the structure. Weathering has increased the porosity; connected and unconnected pore spaces filled with clay minerals are very common. Interpretation of x-ray patterns identified the dominant clay mineral as montmorillonite (Table 3). Thin sections from Zone Ia show that perlite is the major constituent, averaging 72 percent by volume of the rock (Table 5). The groundmass is slightly devitrified and contains abundant microlites, locally oriented subparallel to each other creating a slightly trachytic texture. There are occasional unconnected vesicules, most likely gas cavities. In Zone II the groundmass has been oxidized to a light reddish brown and changed, in part, to a mixture of clay minerals. The phenocrysts remain relatively unaffected, except that the edges of most of the magnetite grains are oxidized. Connected and unconnected pore spaces are partly or entirely filled with clay minerals, calcite, and iron oxides. Perlitic cracks in the groundmass are generally not discernible. There is evidence of hydrothermal alteration in some zones: opal, dolomite, and chlorite occur sporadically.

In Zone IV there is moderate to slight hydrothermal alteration of the groundmass to clay minerals, and alteration of plagioclase, biotite, hornblende, and hypersthene minerals to dolomite, calcite, epidote and chlorite. Voids in the rock are mostly filled with calcite.

Physical properties. Weathering, oxidation, and hydrothermal alteration have changed the physical properties of the dacite. The degree of change caused by these geologic agents in order of increasing effectiveness is 1) hydrothermal alteration with no associated weathering, 2) hydrothermal alteration with associated oxidation and moderate weathering, and 3) severe weathering. Table 4 lists the physical properties of core samples taken from each of the zones shown in figure 3.

The average porosity of Zone I is 18.6 percent, indicating almost 1/5 of the rock consists of some kind of void space. The compressional and shear velocities and elastic constants are low compared to fresh dacite and fall in the range characteristic of many bedded tuffs in southern Nevada. The average static Young's modulus value is 620,000 psi lower than the dynamic value, and probably reflects the closing of voids under initial loading during static testing. The unconfined compressive strength is almost half the strength of fresh dacite.

In Zone Ia the average porosity of the fresh dacite is 6.2 percent and probably represents the voids created by gas cavities and perlitic cracks that are observed in thin sections. The compressional and shear velocities in Zone Ia are 60 percent higher and the dynamic elastic constants are 1/3 higher than those of the severely to moderately weathered rock of Zone I.

The physical properties of the core from Zone II show improved values over those of the more weathered core from Zone I. The average compressional velocity of core from Zone II is 25 percent higher than that of core from Zone I. Total average porosity of the Zone II core has decreased 40 percent, whereas average dynamic Young's modulus and compressive strength have increased 40 percent. A much greater increase occurs between static Young's modulus from the two zones: Zone II averaging 2/3 higher than Zone I.

In Zone III there is a slight decrease in average porosity and an increase in average dynamic elastic constants compared to Zone II, but the average static values of Young's modulus and compressive strength are lower. The layered oxidized-hydrothermally altered (light reddish brown and bluish gray) character of the rock may create an anisotropic condition that imparts a slightly lower strength and elasticity to the cores under static loading.

In Zone IV hydrothermal alteration has increased the average porosity and lowered the average dynamic Young's modulus of the original rock by 40 percent. The average compressional velocity of cores from Zone IV is 25 percent less than the fresh dacite from Zone Ia. Although no static tests were made on the fresh, unaltered dacite, it is safe to assume that alteration has also decreased the compressive strength and static Young's modulus. When compared to properties of the slightly to moderately weathered rock of Zone II, the nonweathered hydrothermally altered rock of Zone IV has higher average compressive strength and elastic values and lower average porosities. There is evidence that Zone II may have been subjected to some hydrothermal alteration, but the added effects of oxidation in the perched water zone, higher joint intensity, and weathering have reduced the competency of the rock in this zone.

<u>Magnetic properties</u>. Magnetic susceptibility is the ratio of intensity of rock magnetization to the magnetizing (earth's) field defined with respect to unit volume (Chapman and Bartels, 1961). In rock, magnetite is the major constituent having magnetic properties, therefore, magnetic susceptibility reflects mostly the volume of magnetite in rock. Magnetite phenocrysts in the dacite average 1.9 percent by volume, in addition, cryptocrystalline magnetite also occurs in the glass matrix (Table 5).

Referring to Table 4, the magnetic susceptibility values of the dacite show interesting variations from zone to zone. Zone I and Zone Ia have high magnetic susceptibility values averaging 1,325 and 1,768 x 10^{-6} cgs units respectively. The light gray color and core descriptions (Table 1) do not indicate any great amount of oxidization in this section. The regional arid climate of the desert apparently has not favored oxidation of the magnetite crystals or cryptocrystalline magnetite in the matrix above the water table. However, on the other hand, it has not retarded chemical weathering of the glassy matrix and feldspar crystals into clay minerals. Zone II and Zone III have low magnetic susceptibility values averaging 256 and 476 x 10^{-6} cgs units respectively. The light reddish brown color of the rock, core description and thin section examination indicate that much of the magnetite has been oxidized into nonmagnetitic hematite in these zones, especially throughout number II. This oxidized section lies in the perched water zone where intermittent wetting and drying of the rock due to fluctuating water levels has created an oxidizing environment. Zone IV is hydrothermally altered but generally unweathered. Color, core description and thin section study show that the magnetite is still relatively fresh. The high magnetic susceptibility reading, averaging 1,508 x 10^{-6} cgs units, attests to the nonoxidized condition of the rock.

The magnetic properties of the dacite suggest that low magnetic susceptibility values reflect oxidation of magnetite in the rock, caused, in this case, by a local perched water zone. On the contrary, desert weathering of the dacite above the perched water and hydrothermal alteration of the rock have not appreciably decreased the magnetite content as shown by the high magnetic susceptibility values.

Underground in-place rock conditions. Mapping of the Pluto entry shaft sunk through Zone I confirmed that the rock was unstable. Overbreak during mining operations was common. The rock was punky and generally incompetent, requiring extensive support by steel sets and timbering. Exposure to the dry desert air caused shrinkage of the clay minerals in the rock, resulting in much sloughing of the wall rock. The high joint intensity of the dacite augmented the already weakened condition of the rock, encouraging slabs and blocks to break out along the joint planes. The fresh dacite blocks of Zone Ia were conspicuous in the shaft, usually standing out as ledges with considerable undercaving of the surrounding weathered rock. Examination of the pilot chamber, constructed in the upper part of Zone II, showed that the rock stood up well. Three joint sets mapped in the chamber have high angle northeast and northwest, and low angle north-south orientations. The intersection of the high angle and low angle joint sets, however, form discrete blocks, ranging from 1 to 3 feet on a side, that disrupt the continuity of the rock mass. A seismic survey conducted in the chamber showed that in-place dynamic Young's modulus values averaged 2.85 x 10^6 psi (R. A. Black and D. R. Cunningham, USGS, oral commun., 1963). The Young's modulus of 12 core samples taken from the chamber zone, however, averaged 4.11 x 10^6 psi. The 30 percent reduction of in-place dynamic Young's modulus values can, therefore, be directly attributed to the effect of jointing in the rock.

Interrelation of physical properties

Table 4 shows that the elastic constants and unconfined compressive strength values of dacite increase with corresponding decrease of porosity in the rock. Likewise both the strength and elasticity of the dacite increase with corresponding increasing dry bulk densities. The observations suggest that the density and amount of pore space in the dacite affect other rock properties. Further examination of Table 4 seems to indicate that a general direct relation also exists between velocities, elastic moduli and unconfined compressive strengths. The analytical data warrant statistical treatment to calculate the degree of interdependence among the rock properties and to see if an easily determined property, such as porosity or density, correlates well with the more complex Young's modulus and unconfined compressive strength.

A least-squares regression program, designed for the Burroughs 5500 computer, ran all possible combinations of the physical property tests made on the dacite cores. The computer calculated both linear and log-linear relations and designated the curves of best fit. Figures 4 through 20 present the results.

The following conclusions from the least-squares regression study are considered by the author to be significant:

1. Porosity has a greater influence than density on the velocities, elastic moduli and uncompressive strength of the dacite. The porosities range between 5.2 and 19.2 percent. Whether porosities below 5.2 percent continue to have more influence than density on rock properties is unknown.

2. The best statistical fit between porosity and elastic moduli, velocities, and strength is log-linear in the range of properties tested, where porosity is linear and the other rock properties are logarithmic.

3. Porosity bears an inverse relation to velocities, elastic constants, and strength, that is, the greater the porosity, the lower the other property values. Porosity is detrimental to the competency of the dacite.

4. Density is directly related to velocities, elastic moduli and compressive strength, that is, the more competent dacite samples have higher densities.

5. Porosity values can be used to make reasonable and rapid predictions of dacite physical properties.

6. Significant correlations exist between static and dynamic elastic moduli, that is, static Young's modulus correlates with dynamic Young's modulus.

7. Static elastic moduli values are generally lower than dynamic elastic moduli values.

8. Static values have more scatter than dynamic values. This can be attributed to the static loading test method that is strongly influenced by anisotropic conditions in rock samples.

9. The directional orientation of linear features in test samples affects the physical property results. Table 6 shows that orienting the flow-banding perpendicular to the pulse direction in dynamic testing gives the lowest elastic constants.

10. Unconfined compressive strength and elastic moduli are directly related, that is, higher strength samples have correspondingly higher elastic moduli.

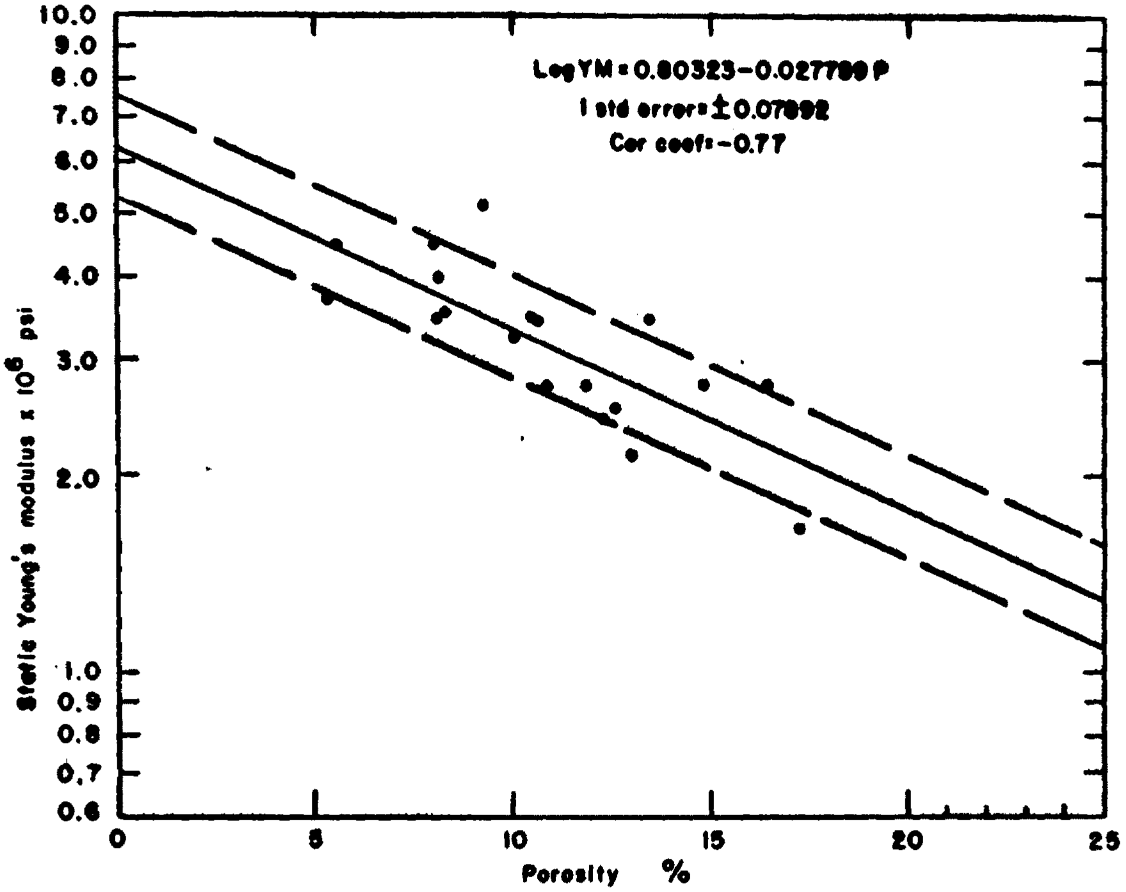


Figure 4.--Static Young's modulus vs. porosity of 19 dacite samples. (log-linear).

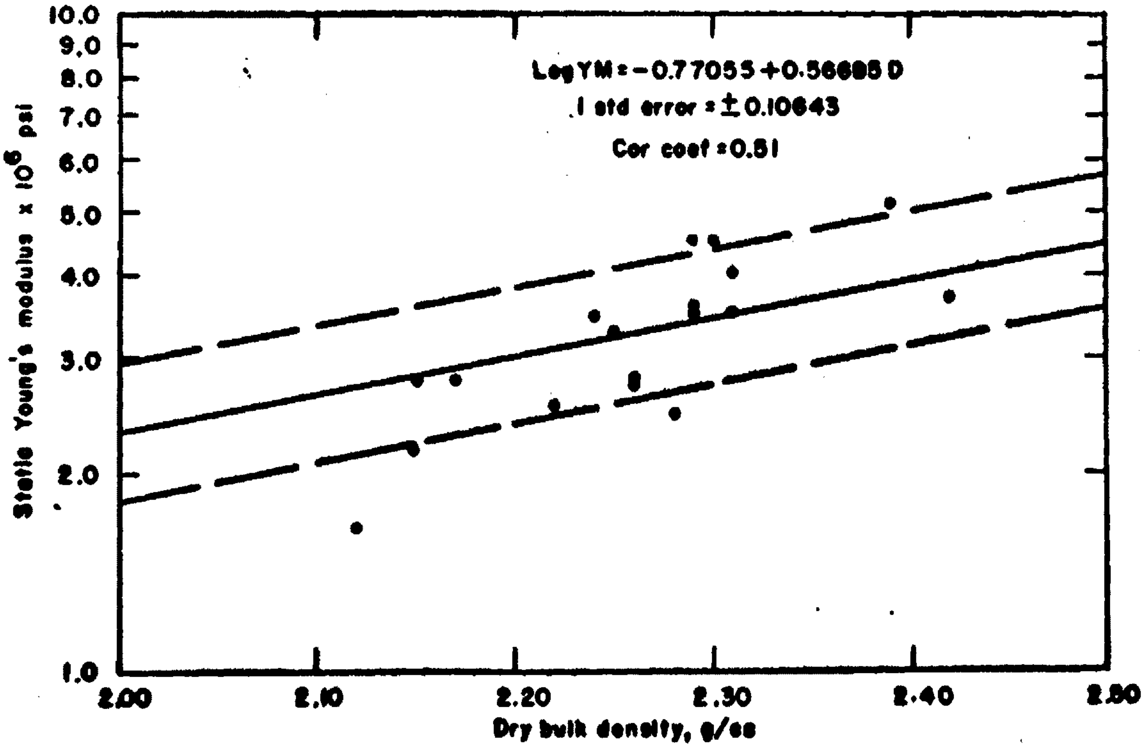
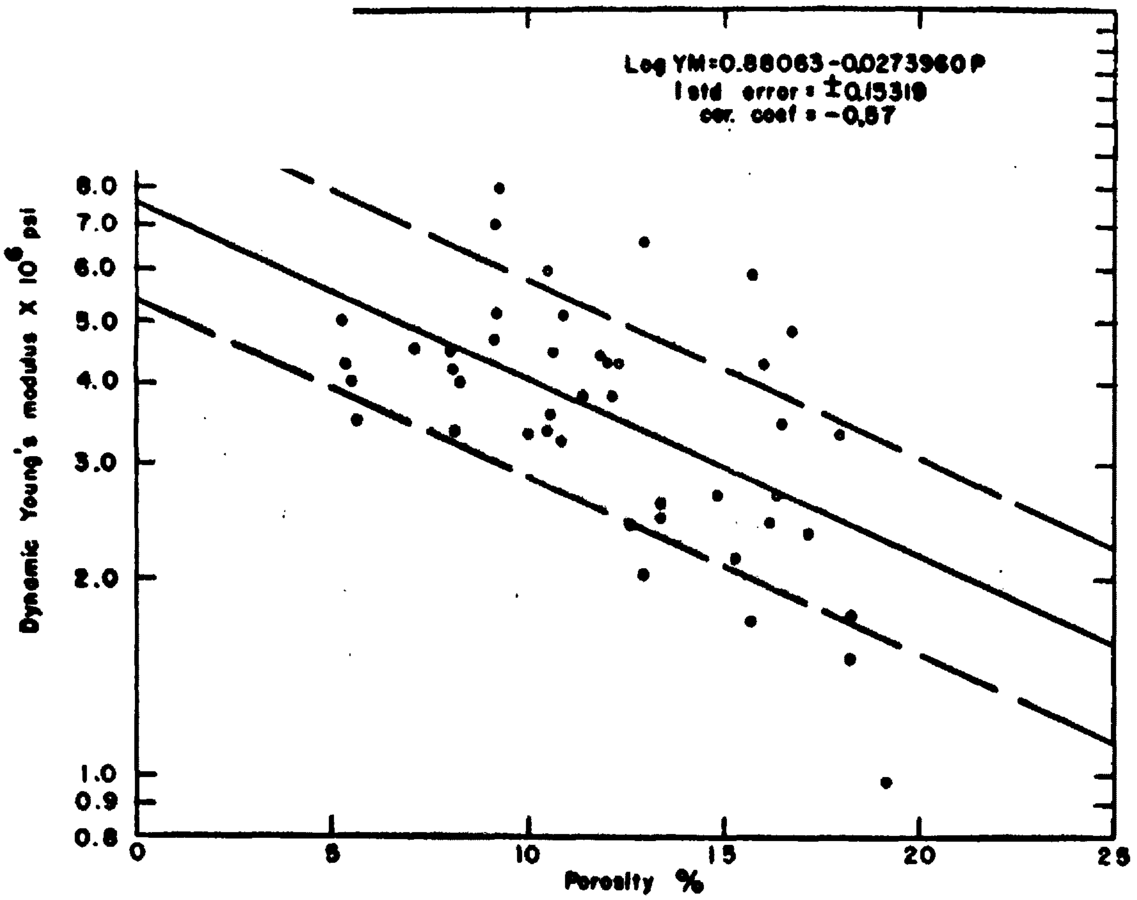


Figure 5.--Static Young's modulus vs. dry bulk density of 19 dacite samples (log-linear).



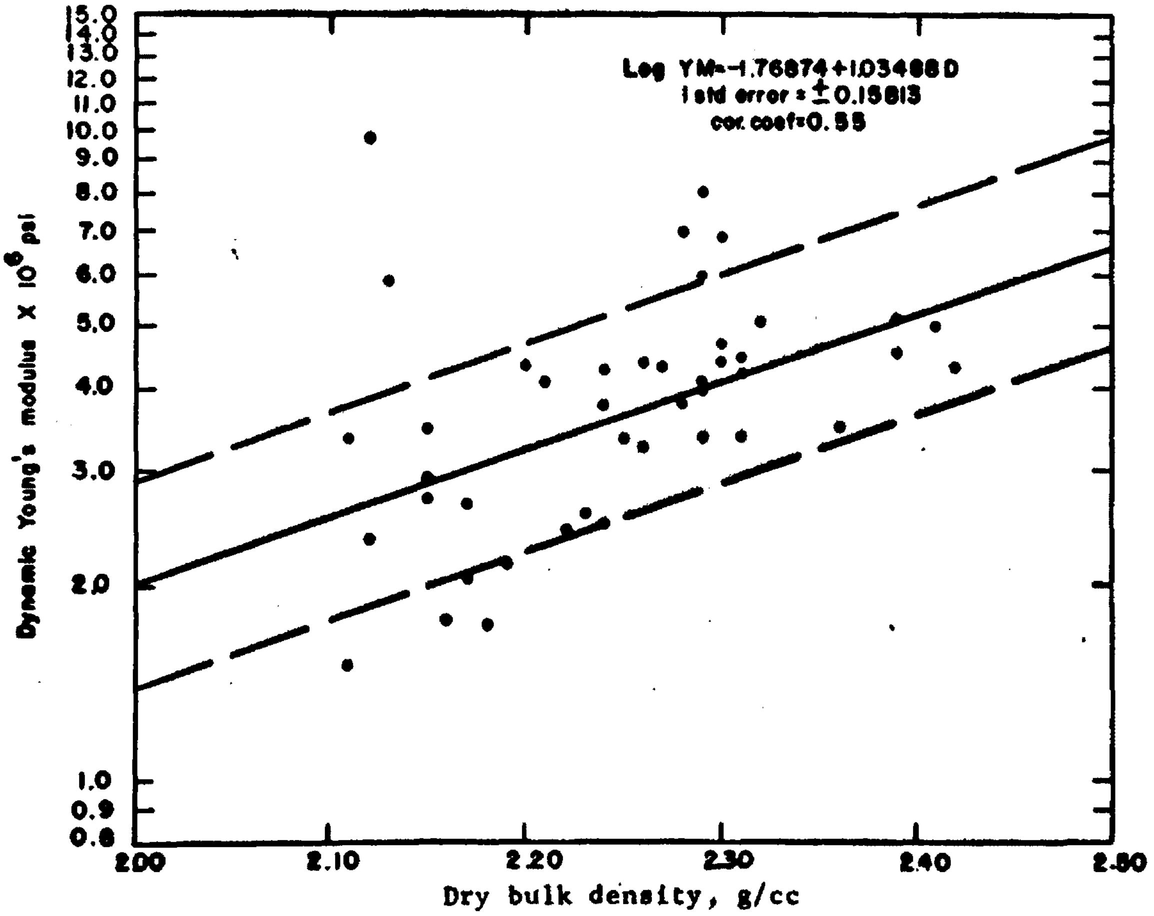


Figure 6 (upper graph).--Dynamic Young's modulus vs. porosity of 44 dacite samples (log-linear).

Figure 7 (lower graph).--Dynamic Young's modulus vs. dry bulk density of 44 dacite samples (log-linear).

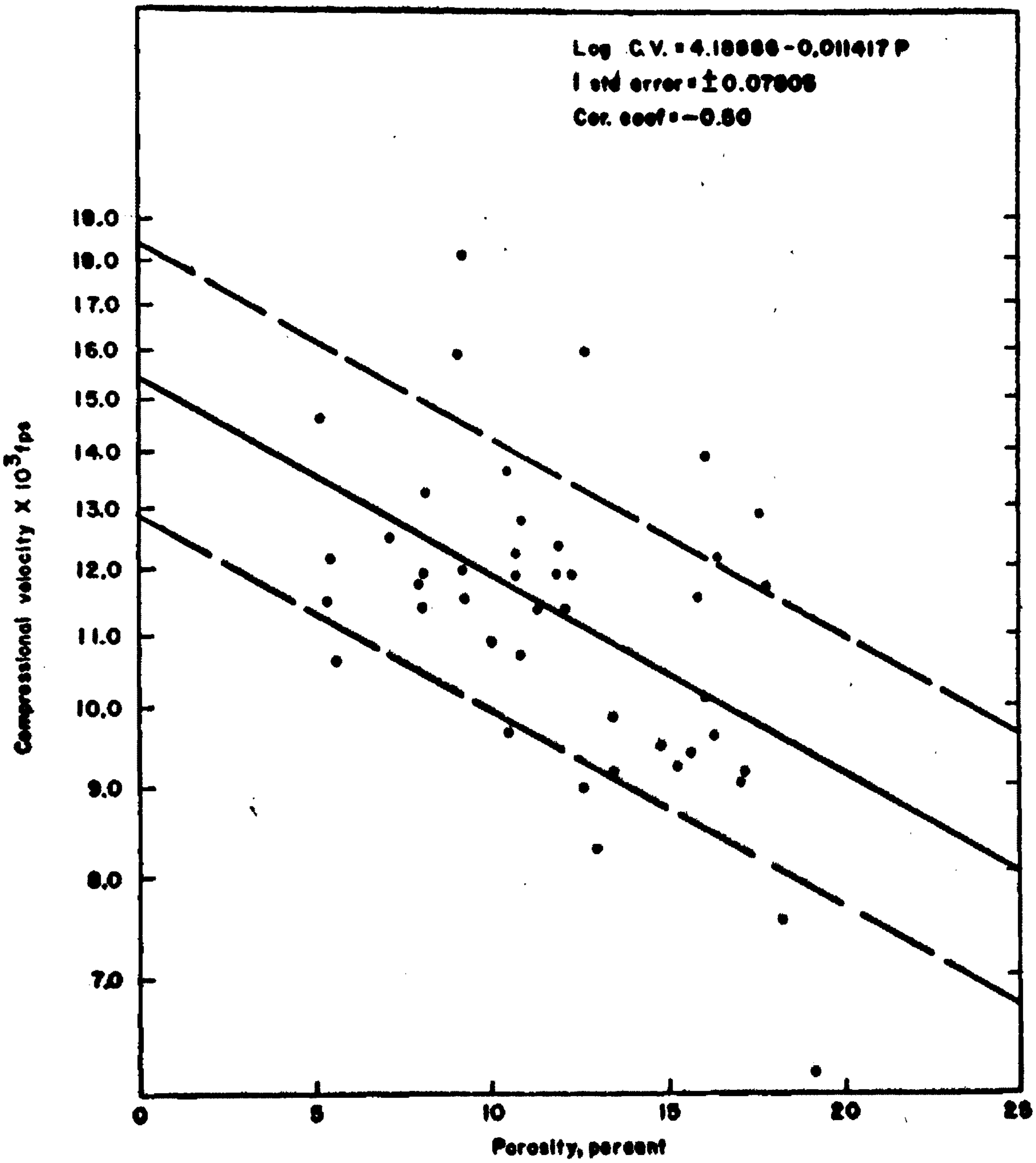


Figure 8.--Compressional velocity vs. porosity of 44 dacite samples (log-linear).

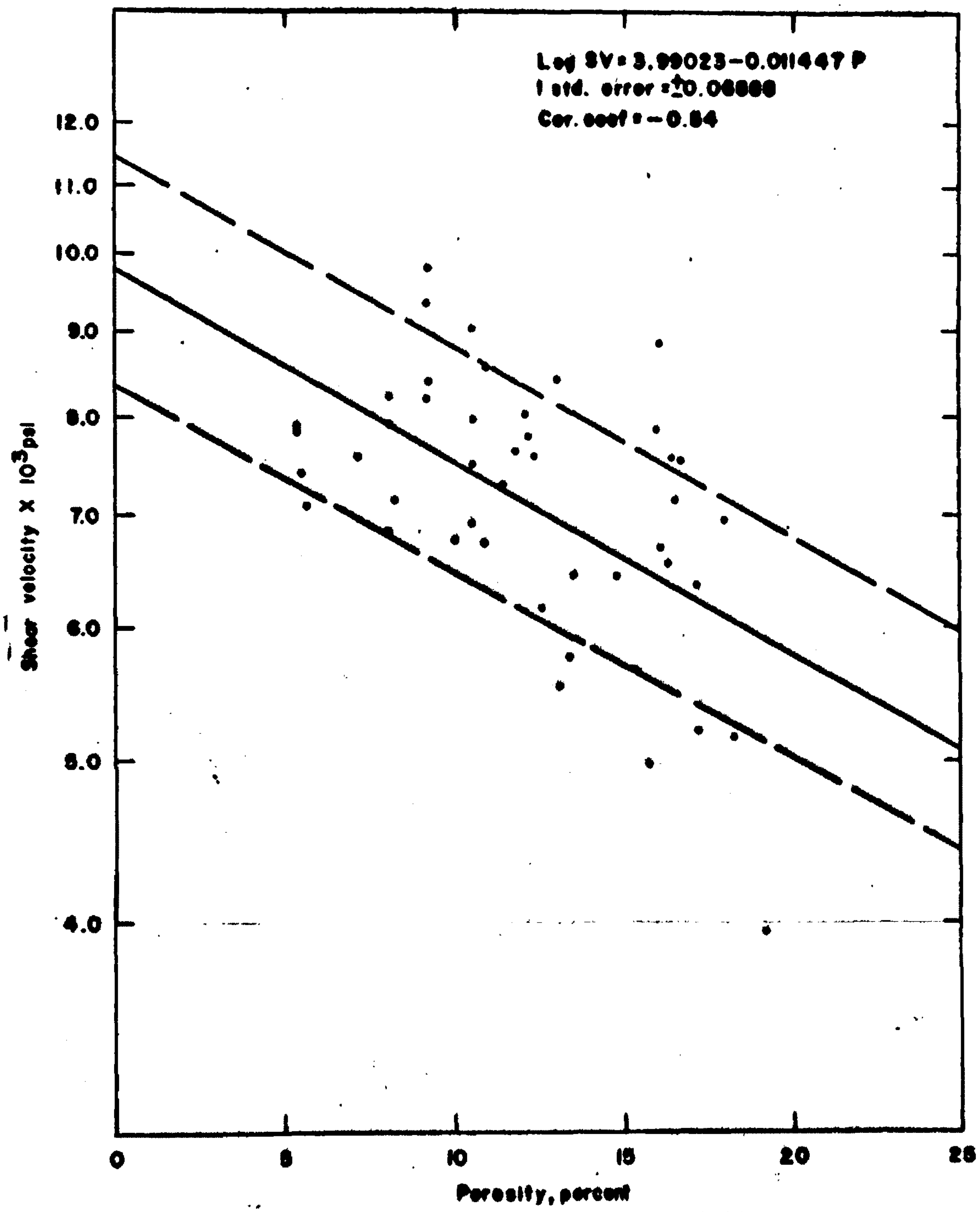


Figure 9.--Shear velocity vs. porosity of 44 dacite samples (log-linear).

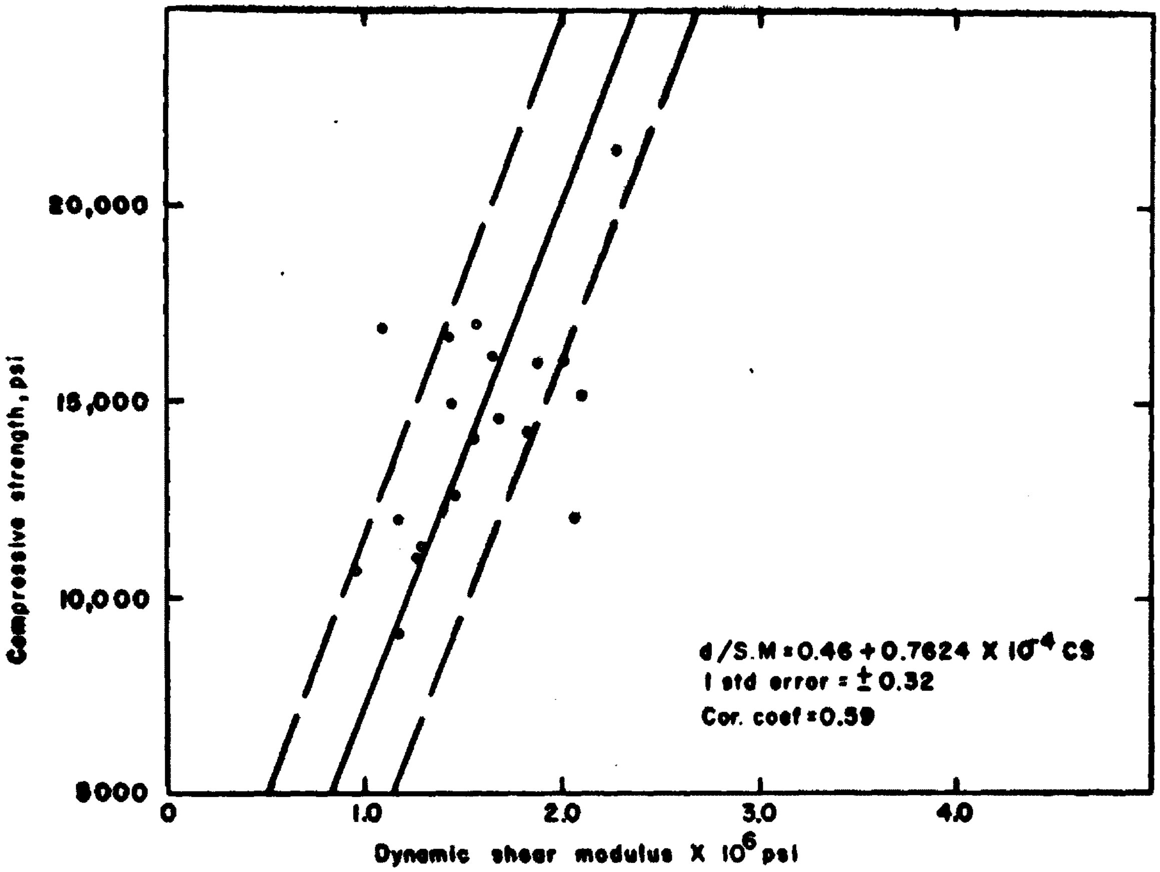


Figure 10.--Unconfined Compressive strength vs. dynamic shear modulus of 19 dacite samples (linear).

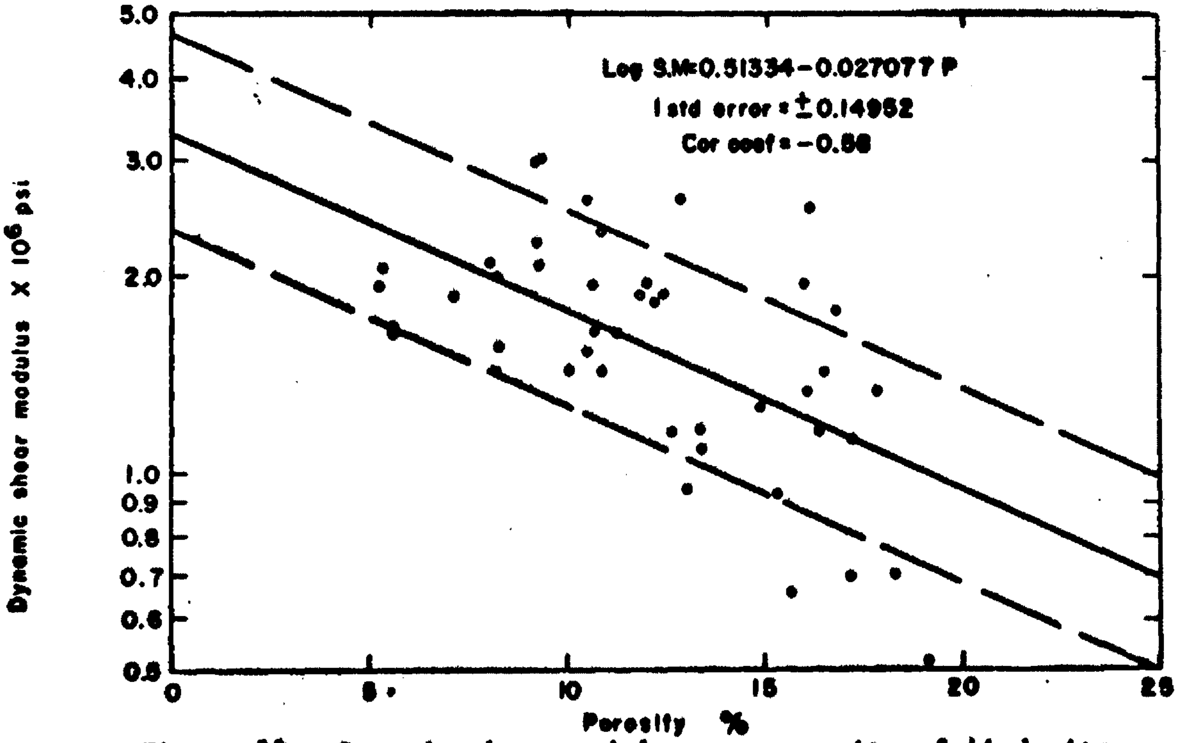


Figure 11.--Dynamic shear modulus vs. porosity of 44 dacite samples (log-linear).

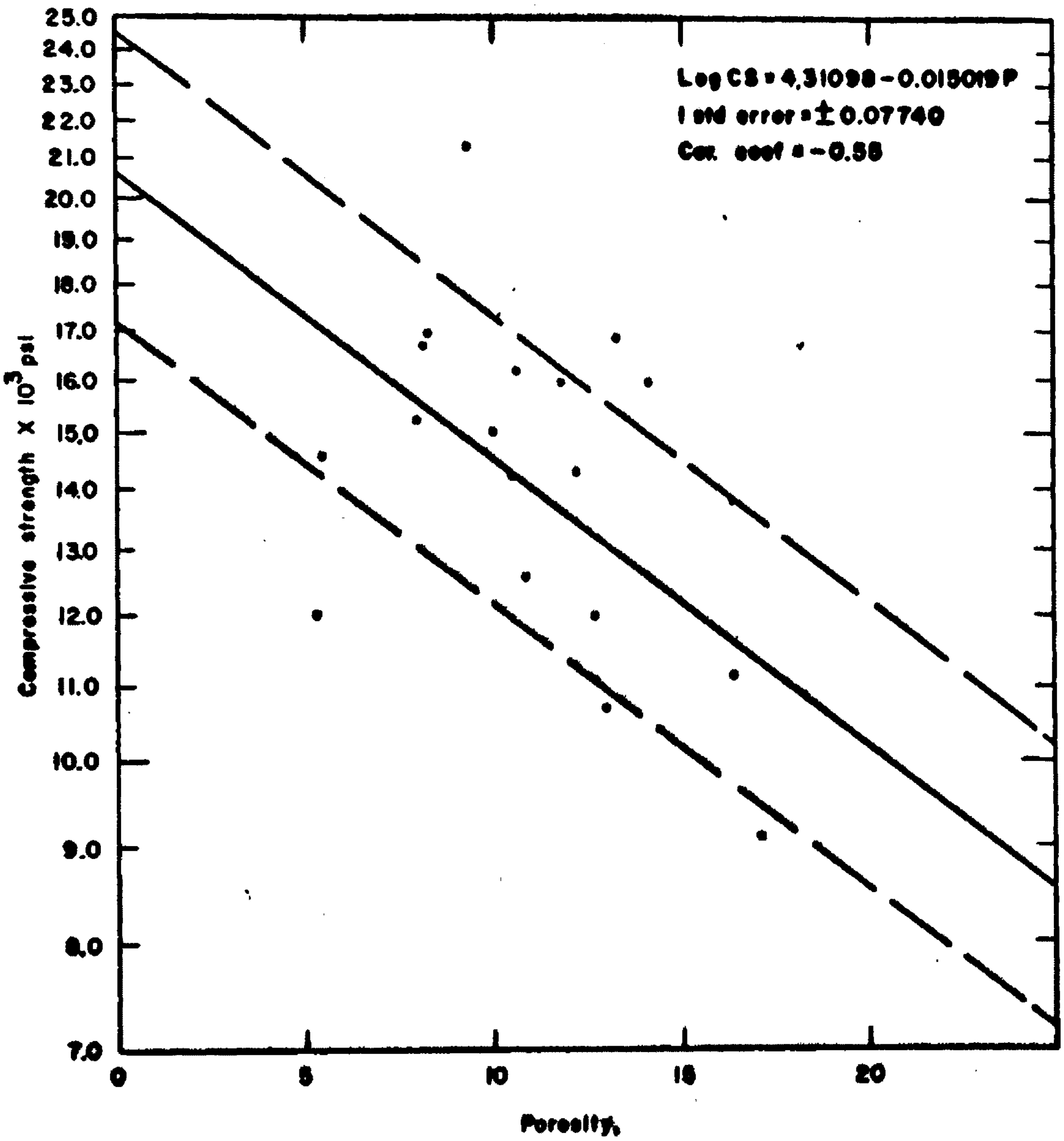


Figure 12.--Unconfined compressive strength vs. porosity of 19 dacite samples (log-linear).

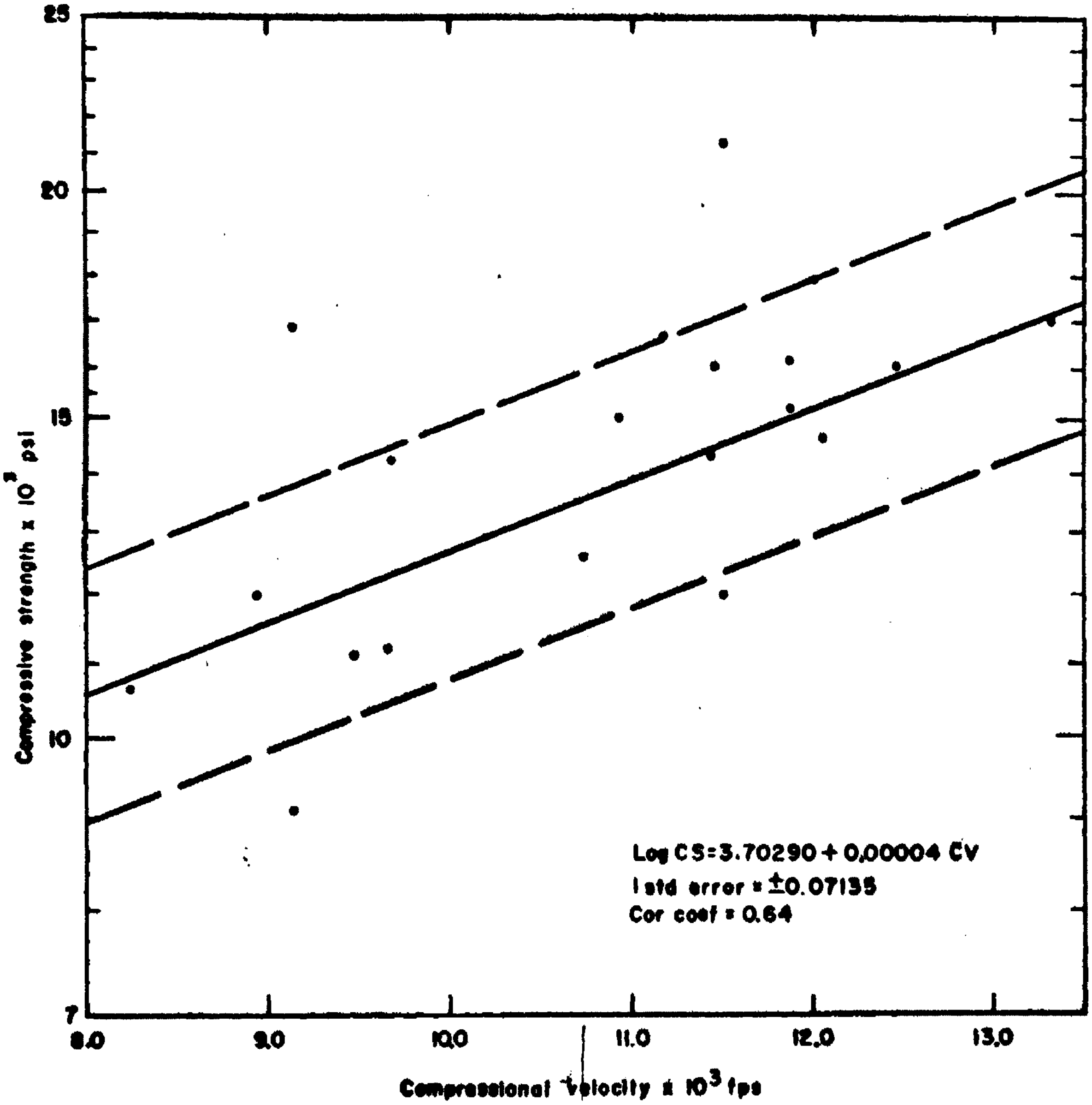


Figure 13.--Unconfined compressive strength vs. compressional velocity of 19 dacite samples (log-linear).

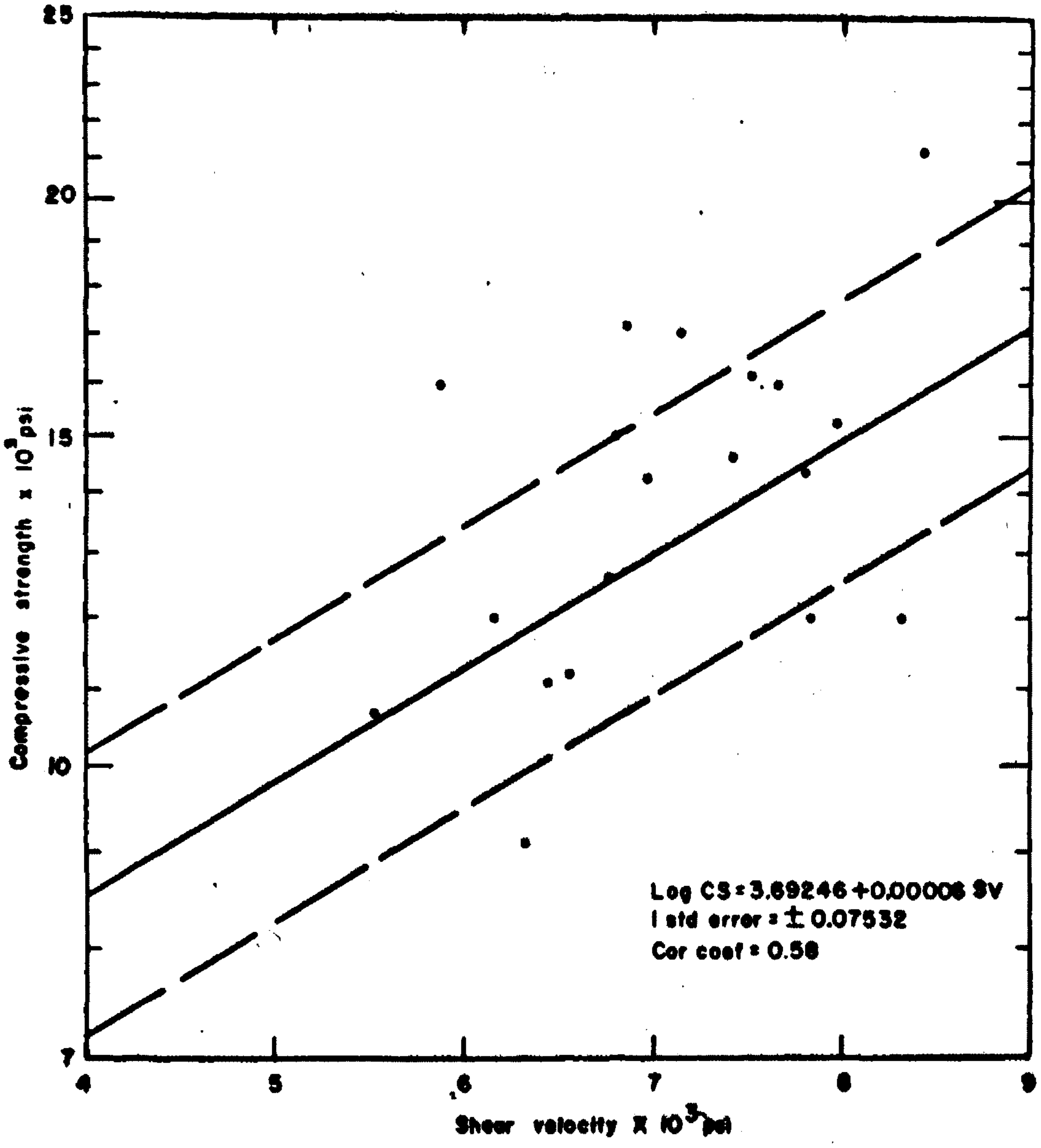
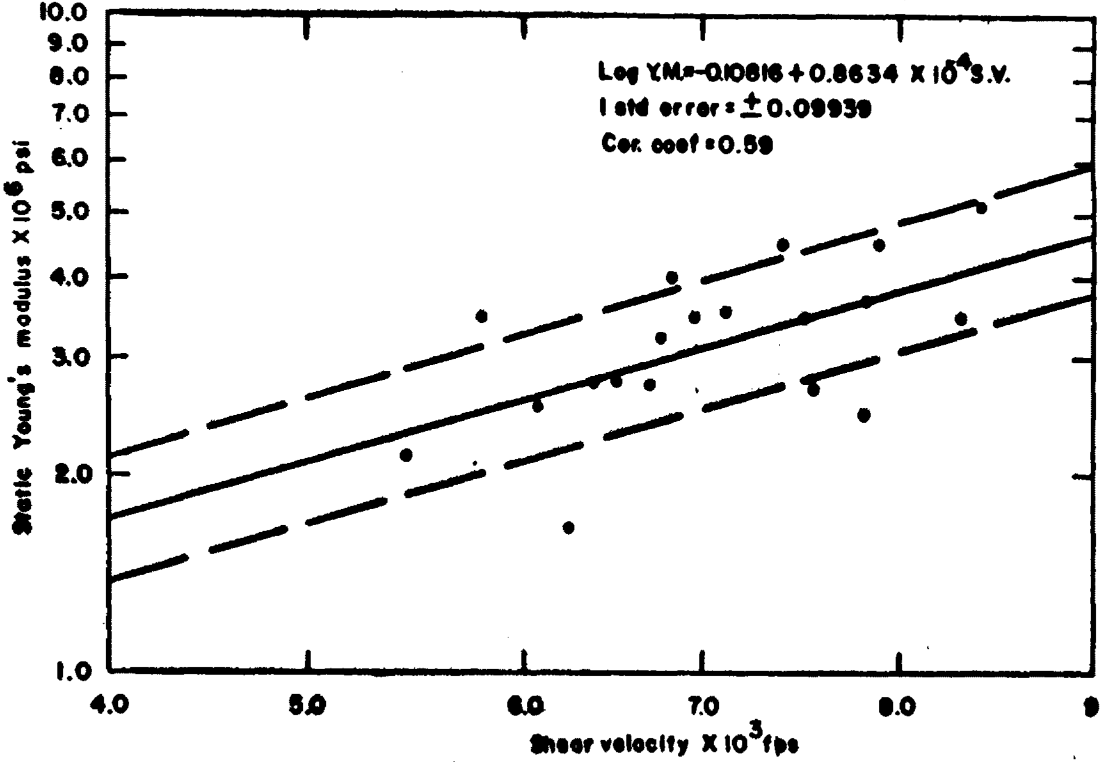


Figure 14.--Unconfined compressive strength vs. shear velocity of 19 dacite samples (log-linear).



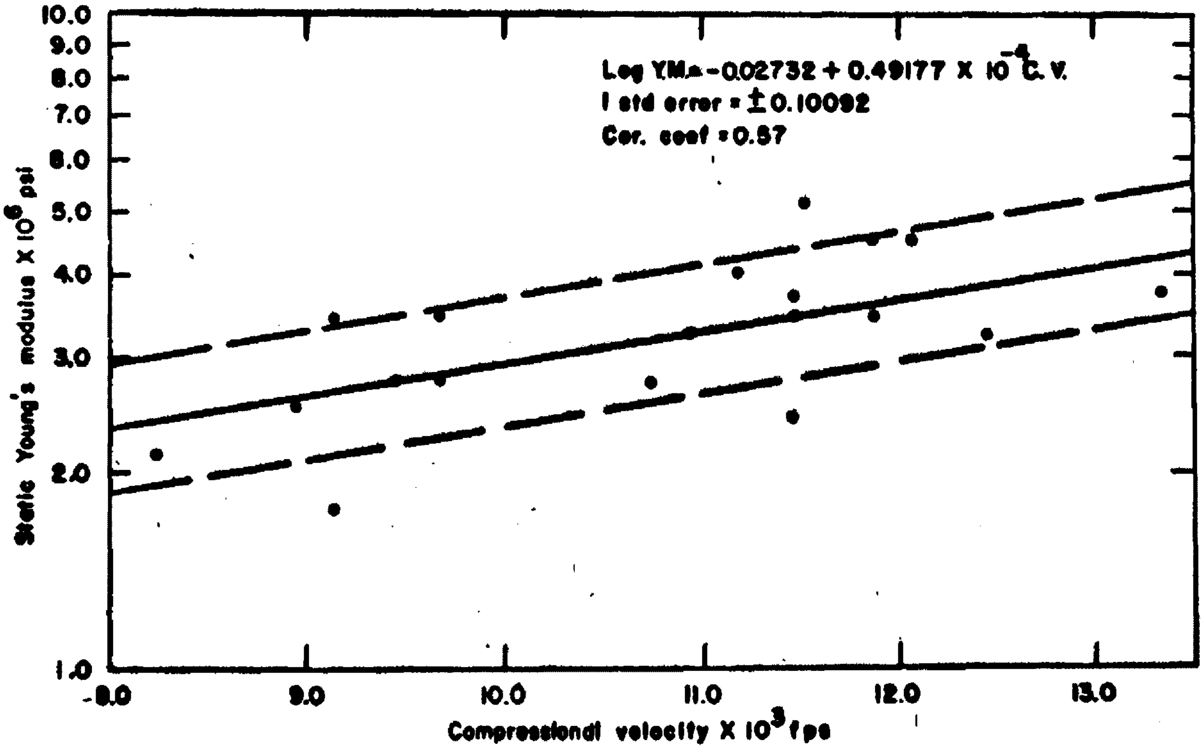
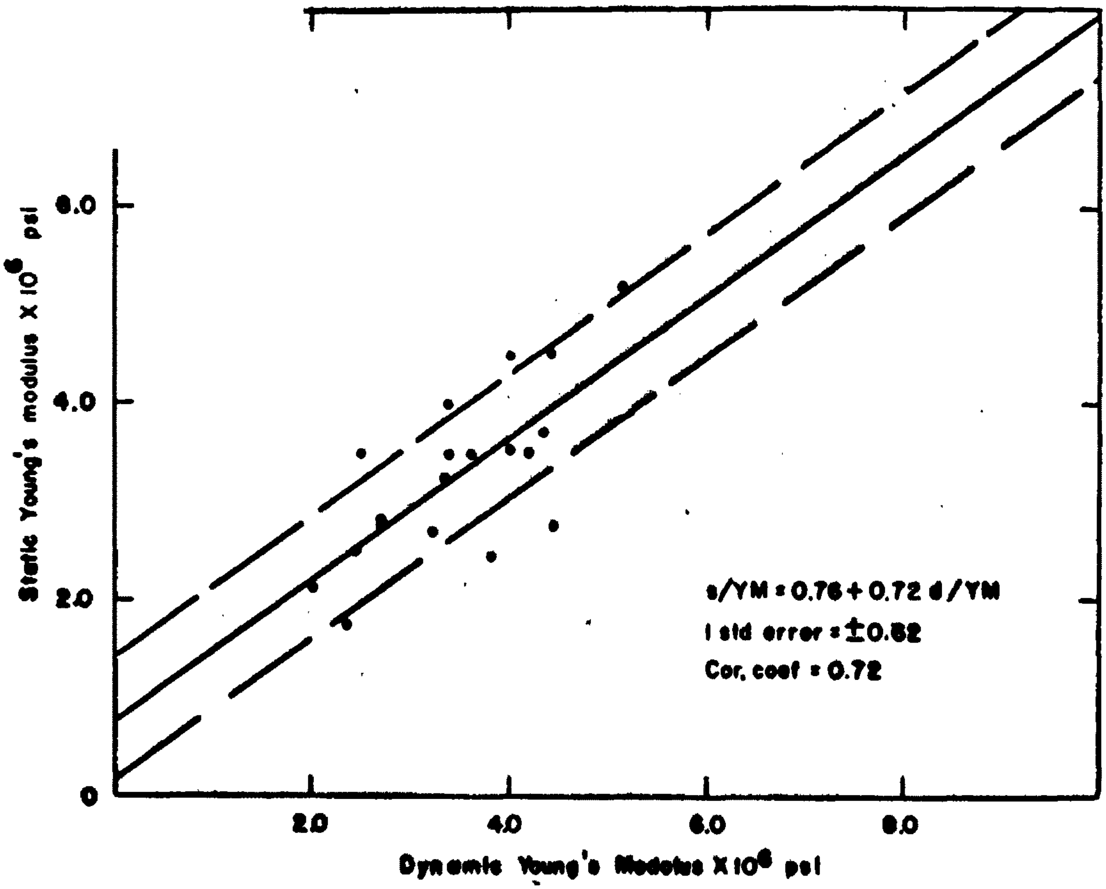


Figure 15 (upper graph).--Static Young's modulus vs. shear velocity of 19 daci samples (log-linear).

Figure 16 (lower graph).--Static Young's modulus vs. compressional velocity of of 19 dacite samples (log-linear).



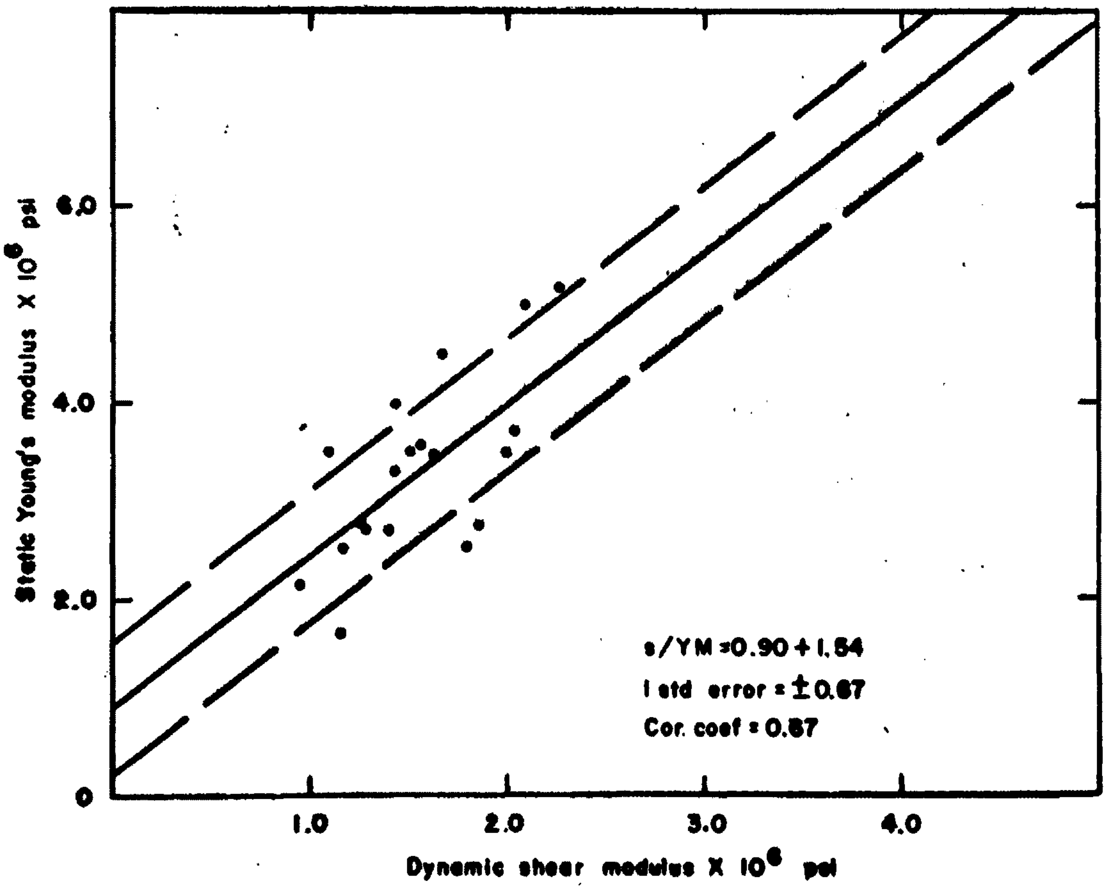
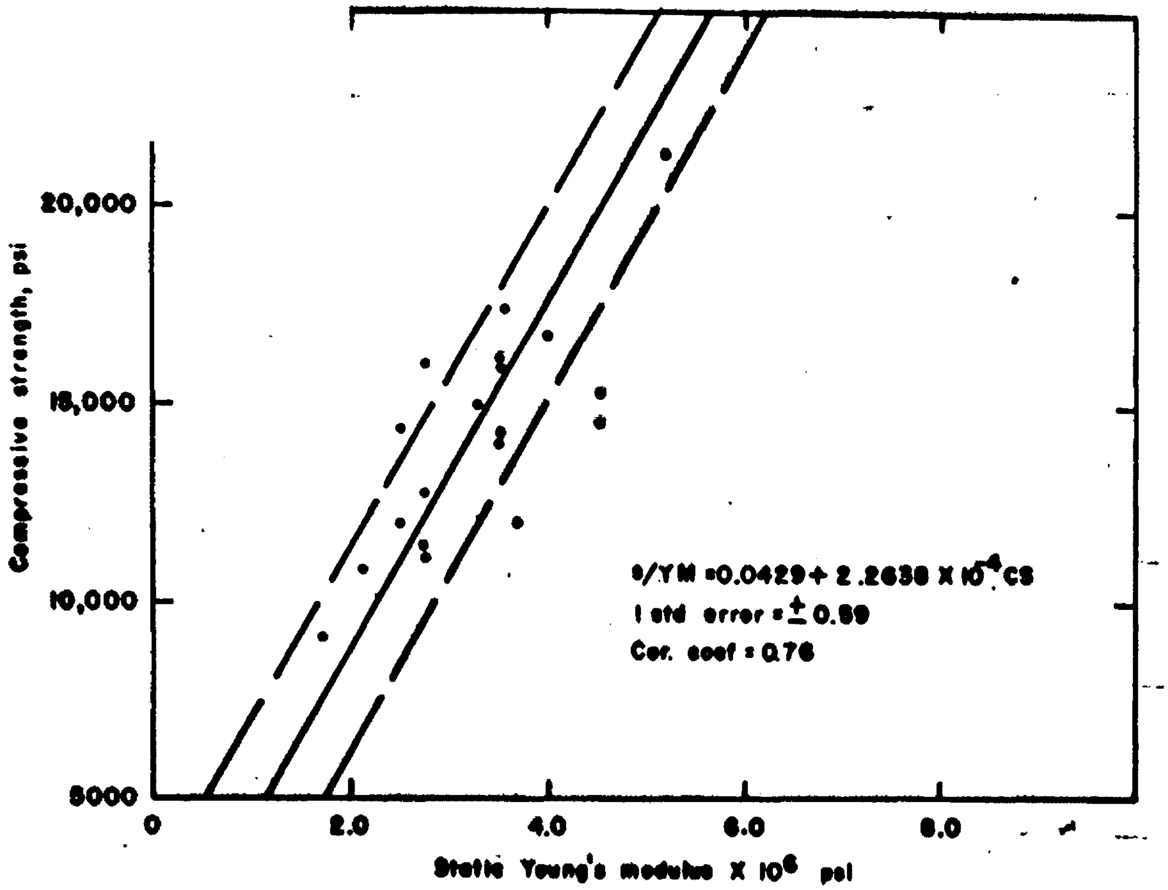


Figure 17 (upper graph).--Static Young's modulus vs. dynamic Young's modulus of 19 dacite samples (linear).

Figure 18 (lower graph).--Static Young's modulus vs. dynamic shear modulus of 19 dacite samples (linear).



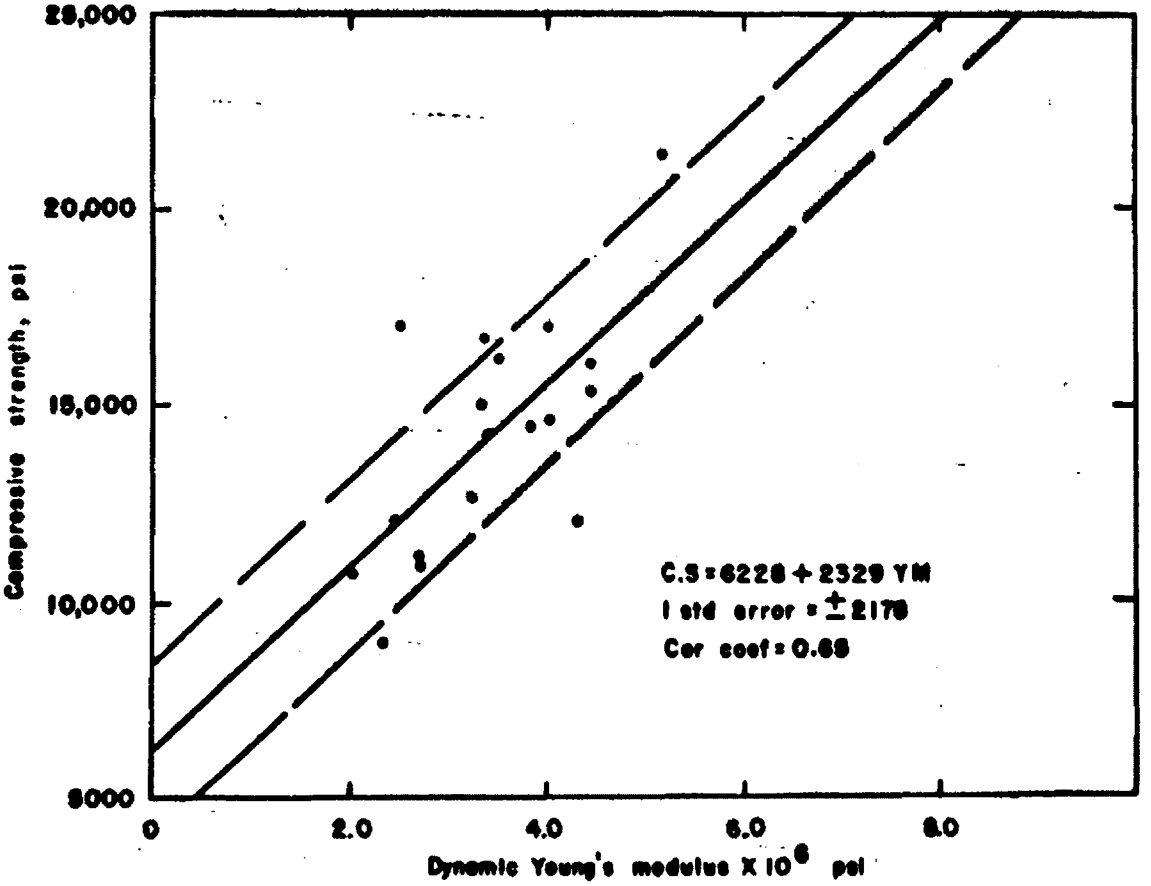


Figure 19 (upper graph).--Unconfined compressive strength vs. static Young's modulus of 19 dacite samples (linear).

Figure 20 (lower graph).--Unconfined compressive strength vs. dynamic Young's modulus of 19 dacite samples (linear).

Table 6.--Variations in dynamic physical properties caused by orienting flow banding in a dacite porphyry test sample parallel, perpendicular, and 45 degrees to direction of pulse.

/̲Dynamic pulse method, air-dried samples̲7

Orientation of test sample's flow banding to pulse	Compressional velocity (ft/sec)	Shear velocity (ft/sec)	Poisson's ratio	Young's modulus	Shear modulus	Bulk modulus
parallel	13,800	8,600	0.18	5.5	2.3	2.9
perpendicular	13,000	8,000	0.19	4.8	2.0	2.6
45°	13,900	8,700	0.19	5.6	2.4	3.0

INTERRELATION OF GRANITE IN-PLACE ROCK STABILITY TO LOCAL GEOLOGY

Introduction

A unique structure constructed 300 feet below ground surface in a granitic rock required an extensive geologic program that followed the project from the drawing board to the completion of mining operations. A 380-foot entry shaft, 500 feet of communication drifts and a 70-foot diameter hemisphere with a near vertical flat face had to be excavated in a strongly jointed medium that was cut by faults, shears and altered zones. The critical factors in the hemisphere's design was the arch in the crown that was mathematically calculated to give maximum strength to the structure, and a flat face that would have a neat surface not varying more than 1 foot in overbreak. From the start the geologic approach was to 1) determine the dominant joint orientations and then locate a single joint plane along which to mine the hemisphere face; the intent being to minimize overbreak, 2) calculate joint and fault orientation and intensity and to locate the site in the least fractured, weathered and altered rock at the planned depth, and 3) avoid ground water.

The project area, situated in the Climax stock at the Nevada Test Site (fig. 1), was mapped for geology at the surface and cored by four 650-foot drill holes before selecting the final location. Examination of the cores provided underground conditions which were translated into engineering and construction predictions. Detailed subsurface mapping was kept current with mining operations and the orientation of the joint plane to be used as the surface for the hemispherical face was chosen from the structure maps. A small exploratory drift at the elevation of the proposed face center was driven until it crossed a suitable joint plane. Analysis of joints from oriented cores and surface maps indicated a favorable potential joint orientation having a strike of N40°E and a dip of 70°SE. The joint selected had a strike of N44°E and a dip of 74°SE. The hemisphere was located in competent rock and was successfully excavated, meeting all design criteria.

Geology of the Climax stock

Intrusive rocks. The Climax stock is a granitic intrusive, roughly elliptical in shape (Houser and Poole, 1960). Its surface exposure is about 1 1/2 square miles in area. The igneous rocks of the stock are an older porphyritic fine- to medium-grained quartz monzonite, and a younger equigranular granodiorite (fig. 21). The hemisphere is in the quartz monzonite phase.

Structure. The rock of the stock is jointed, faulted, and sheared. The joints and faults generally strike northeast or northwest and have two distinct angles of dip. One joint and fault set dips steeply and strikes northeast and northwest; the other joint and fault set dips at a low angle and strikes northwest.

Ground water. Walker (1962) states that ground water is thought to exist in the stock only locally where the rock is most fractured. The water supply is replenished from precipitation in the immediate area. There is apparently no extensive zone of saturation. Where ground water is present it is limited in quantity.

Description of the porphyritic quartz monzonite. The quartz monzonite ("granite") which encloses the hemisphere is very light gray to bluish white (Table 7). The essential mineral constituents of the rock are quartz, feldspar, biotite and hornblende. Feldspar phenocrysts, as much as 2 inches in length, occur throughout most of the rock. The rock is jointed

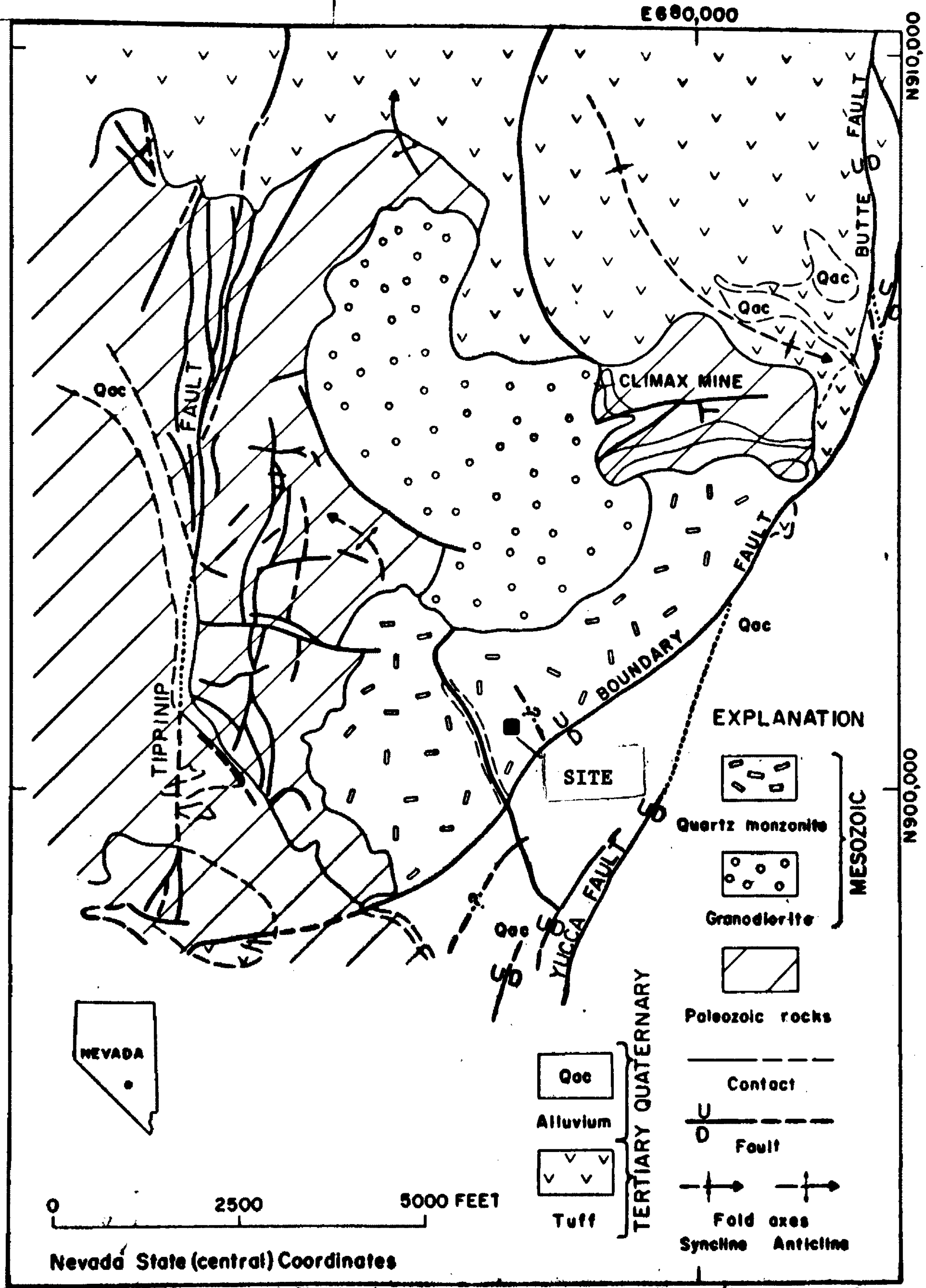


Figure 21.--Geologic map of the Climax stock, Nye County, Nevada. (Modified from Barnes and others 1963)

and weathering has occurred along the joints to depths of 300 feet below the surface. The zone of pervasive weathering, however, reaches a maximum of 150 feet below the surface mainly along shear zones. Hydrothermal solutions have introduced secondary quartz, feldspar and pyrite along joint planes.

Rock stability and local geology

A successful engineering geology study related in-place rock stability to local geology of the Climax stock. The program, combining a special core logging technique, statistical analysis of the core data, and underground mapping, correlated core conditions with in situ conditions.

About 2,600 feet of core were taken from four inclined drill holes in the Climax stock as part of the site selection for the underground hemisphere. Previous surface mapping of fractures in the stock determined the orientation of the drill holes so they would intersect the maximum number of joints and faults. The rigid requirements for competent rock needed for the hemisphere demanded accurate predictions of underground conditions from the retrieved core. Since the hemisphere would be built in a single rock type, the major local geologic features that would affect the stability of the granite were weathering, alteration, joints and faults.

Core logging. The most important information needed from the cores was fracture, weathering and alteration data. To get this information, the core from each boring was initially laid out in continuous sequence according to depth, that is, from ground surface to the bottom of the hole. The cores were then divided into "logging units" that segregated more competent zones from less competent zones based on the gross appearance of joint intensity, weathering and faults in the core. The minimum length of a logging unit was set at 10 feet. In addition to recording standard lithologic descriptions of these segregated zones (Table 7), the cores were logged in detail for joint frequency (joints per foot of core), degree of weathering, relative hardness of the rock, percent of core loss, and percent of broken core. Broken core is defined as core that is fragmented by high joint intensity and faults into pieces less than 3 inches in size.

In order to permit later computer analyses of all the geologic factors recorded in the core, the weathering and hardness descriptions were quantified by assigning numerical values of "1" for very hard and unweathered, "2" for hard and slightly weathered, "3" for intermediate hardness and moderately weathered and "4" for incompetent and severely weathered rock. Comparison of core samples to an unweathered, very hard, unfractured sample of core determined the value of hardness and weathering to be given to each logging unit. Only those joints which were open or those that were sealed by a soft material such as clay, limonite, or calcite were recorded.

Interpretation of core data. A least-squares regression, programmed for a Burroughs 5500 computer, analyzed the logged-core data, and established that there is a good relation among joint frequency, weathering, hardness, core loss, and broken core. Joint frequency was chosen as the independent variable and the other parameters as the dependent variables in the regression equations. Selection of joint frequency as the independent variable was based on the following considerations: (1) joint frequency is a quantity that can be measured repeatedly by any number of persons, (2) joints are a major factor in contributing to core loss and broken core, (3) joints introduce discontinuities into a rock mass thereby decreasing its competency, and (4) joints provide passageways for water and solutions that can cause weathering and alteration.

Figure 22 presents the results of the least-squares regression analyses of the core data. Significant correlations exist between all variables within the following limits: (1) when the joint frequency ranges between 0 and 8 joints per foot, (2) when the mean value of core loss range between 0 and 25 percent, and (3) when the mean value of broken core ranges between 0 and 34 percent. Outside these limits there is, however, no significant interrelation among the parameters. The values at which correlations no longer exist between joint frequency and the other parameters, therefore, effectively define the conditions under which the core becomes totally incompetent.

The statistical information shown on figure 22 suggests that the core can be divided into various levels of competency depending on the interrelation of joint frequency and the four other easily determined logging parameters. A device to show these parameter correlations can be made by establishing a frame of reference in the form of a table that arbitrarily divides rock into eleven "grades" and assigns grade 1 ("poor rock") through grade 10 ("good rock") and grade ∅ (faults) to the eleven divisions. The independent variable of joint frequency can be assigned to grades 1 through 10, by dividing the frequencies within the range of significance (0 to 8 joints per foot) into 10 nearly equal units and placing them alongside the rock grades; 8 joints per foot being assigned to grade 1. The other parameters of hardness, weathering, core loss and broken core can be assigned to their respective grades by referring to the joint frequency units and determining the corresponding value of the dependent parameter from the graphs shown on figure 22.

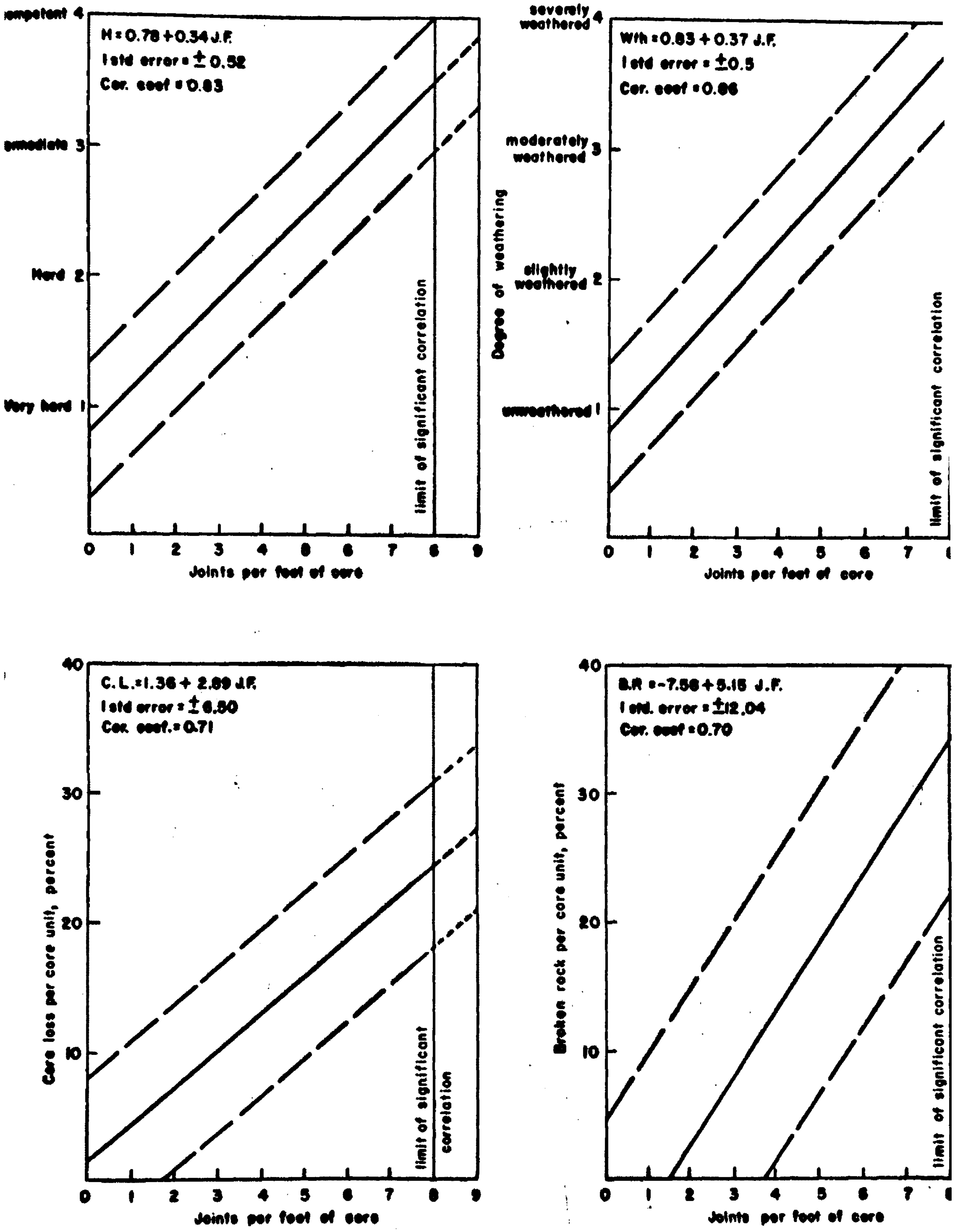


Figure 22.--Correlation curves showing relation of rock hardness, degree of weathering, core loss, and broken core to joint frequency in granitic core.

Table 8 shows the interrelation of geologic parameters for an idealized average core taken from granitic rock. Because the coefficients of correlation between the parameters are excellent, that is all are greater than 0.70, it is reasonable to assume that this table represents a close approximation of conditions for any granitic core. Consequently an index number has been calculated for each grade. The index number is the sum of the numerical values of joint frequency, hardness, weathering, 0.1 of the percent core loss, and 0.1 of the percent broken core assigned to the grade. One tenth of core loss and broken core values are used to keep all figures in the range 0 to 10; joint frequency rarely exceeds 10 joints per foot.

The core index number is used to assign an "idealized" grade to each logging unit of a core by adding together the raw core data in the manner just described. That the index number will be truly representative of a core interval, thereby, allowing assignment of a representative grade to the core is justified by the following: 1) Five parameters, having high degrees of intercorrelation, are all used to describe the core. Extreme values of any one parameter away from the mean will tend to be averaged out by the other parameters when all values are summed to obtain the index number. 2) The high coefficients of correlation indicate that deviation of parameter values from the mean will not be very significant, that is, the core condition will not vary significantly within the limits of one standard error of estimate. One standard error of estimate is shown for the graphs on figure 22 by dashed lines. 3) The core index permits a standard method for calculating the grade of rock. Table 9 shows the interrelation of core parameters for one of the exploratory cores taken from the Climax stock.

Table 8.--Grade of rock table for granite.

In place condition	Rock grade	Joint frequency (joints per foot of core)	Relative rock hardness	Degree of weathering of alteration	Average percent		Index number 1/
					Core loss	Broken core	
Very competent rock, requires no support	10	1.0	Very hard (1)	Unweathered (1)	4	0	<3.4
	9	1.0 - 1.7	Very hard (1)	Unweathered (1)	6	0	≤4.3
	8	1.7 - 2.5	Hard (2)	Slight (2)	8	5	≤7.8
Competent rock, however requires occasional support, some overbreak	7	2.5 - 3.3	Hard (2)	Slight (2)	10	9	≤9.2
	6	3.3 - 4.1	Hard (2)	Slight (2)	13	13	≤10.7
	5	4.1 - 4.8	Hard (2)	Slight (2)	15	16	≤11.9
Generally poor rock, requires support, much overbreak	4	4.8 - 5.6	Intermediate (3)	Moderate (3)	17	20	≤15.3
	3	5.6 - 6.3	Intermediate (3)	Moderate (3)	20	24	≤16.7
Incompetent rock	2	6.3 - 7.1	Intermediate (3)	Moderate (3)	22	28	≤18.1
	1	7.1 - 8.0	Incompetent (4)	Severe (4)	24	33	>18.1
	0		FAULT				

1/ Joint frequency + weathering + hardness + 0.1 core loss + 0.1 broken core.

Table 9. Interrelation of joint frequency, core Loss, broken core weathering, and hardness of a 650-foot granitic core.

core interval (feet)	joint frequency (joints per foot)	core loss (percent)	broken core (percent)	weathering 1/and 2/	hardness 1/and 2/	grade
34 - 68	3.7	8	5	mod	int	5
68 - 88	5.7	10	4	mod	int	4
88 - 96	4.3	10	10	mod	hard	6
96 - 104	3.0	0	0	sli	hard	8
104 - 114	3.4	12	0	mod	hard	6
114 - 132	<- - - - -	- - - - -	FAULT- -	- - - - - - -	- - >	0
132 - 141	4.7	12	3	mod	int	4
141 - 152	<- - - - -	- - - - -	FAULT- -	- - - - - - -	- - >	0
152 - 171	6.7	12	33	sev	inc	2
171 - 192	3.6	10	6	sli	hard	7
192 - 197	7.1	0	29	mod	inc	2
197 - 210	4.1	10	0	sli	very hard	7
210 - 218	7.8	16	35	mod	inc	1
218 - 230	2.9	10	0	sli	very hard	8
230 - 236	4.3	20	9	mod	hard	5
236 - 245	1.6	6	0	un	very hard	9
245 - 250	7.2	13	31	mod	inc	1
250 - 280	2.3	9	0	sli	very hard	8
280 - 301	3.0	16	0	sli	hard	7
301 - 309	1.4	0	0	un	very hard	10

Table 9.Interrelation of joint frequency, core Loss, broken core weathering,and hardness of a 650-foot granitic core.--continued

core interval (feet)	Joint frequency (Joints per foot)	core loss (percent)	broken core (percent)	weathering 1/	hardness 1/	grade
309 - 415	5.6	19	29	mod	int	3
415 - 436	<- - - - - -	- - - - -	- - FAULT- -	- - - - - -	- - >	0
436 - 442	7.1	33	62	mod	int	1
442 - 447	4.4	13	7	sli	hard	6
447 - 496	0.9	3	1	un	very hard	10
496 - 532	2.1	13	3	un	hard	8
532 - 598	1.1	4	2	un	very hard	9
598 - 605	<- - - - - -	- - - - -	- - FAULT- -	- - - - - -	- ->	0
605 - 615	7.6	10	19	sli	int	5
615 - 653	1.6	6	1	un	very hard	9

1/ Code: un, unweathered; sli, slight; mod, moderate; sev, severe; int, intermediate; inc, incompetent.

2/ Numerical assignment: unweathered and very hard--1; slightly weathered and hard--2; moderately weathered and intermediate hardness--3; severely weathered and incompetent--4.

Physical properties. Samples selected from core zones having assigned rock grades were gathered from all four granite cores and sent to the laboratory for both static and dynamic physical property tests. Static and dynamic determinations were made on the same specimens; however, premature failure during loading of seven incompetent samples, having grades 0 to 3 invalidated these static tests.

The physical property values were programmed into a least-squares regression analysis to see what effect fractures and weathering had on physical properties. This was done by comparing the rock properties with their respective rock grade.

Figures 23 through 31 present the results of the computer analyses. The graphs support the following conclusions:

1) Significant correlations exist between physical properties of granite and rock grade, and therefore, between fractures and weathering. The one exception is static bulk modulus which has an apparent low coefficient of correlation.

2) The dynamic physical properties have higher degrees of correlation than static physical properties.

3) Reasonable and immediate estimates of physical properties can be made from data obtained from core logs and rock grade.

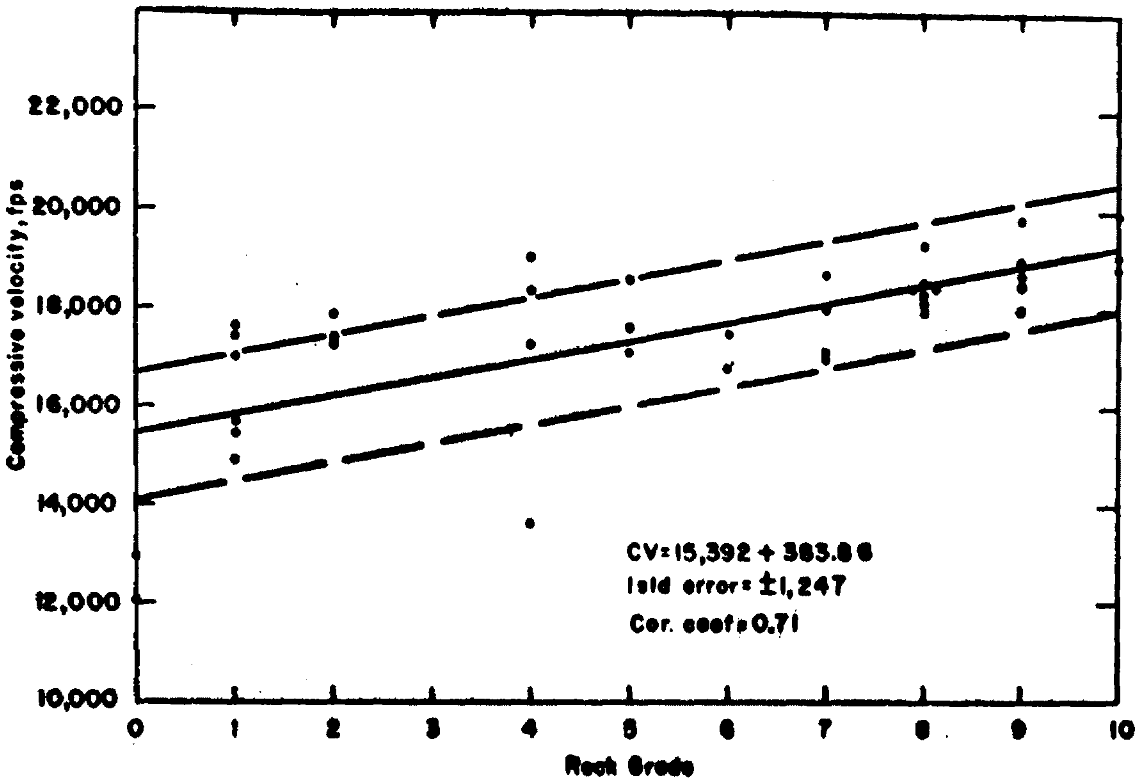


Figure 23.--Compressive velocity vs. rock grade of 39 granitic samples.

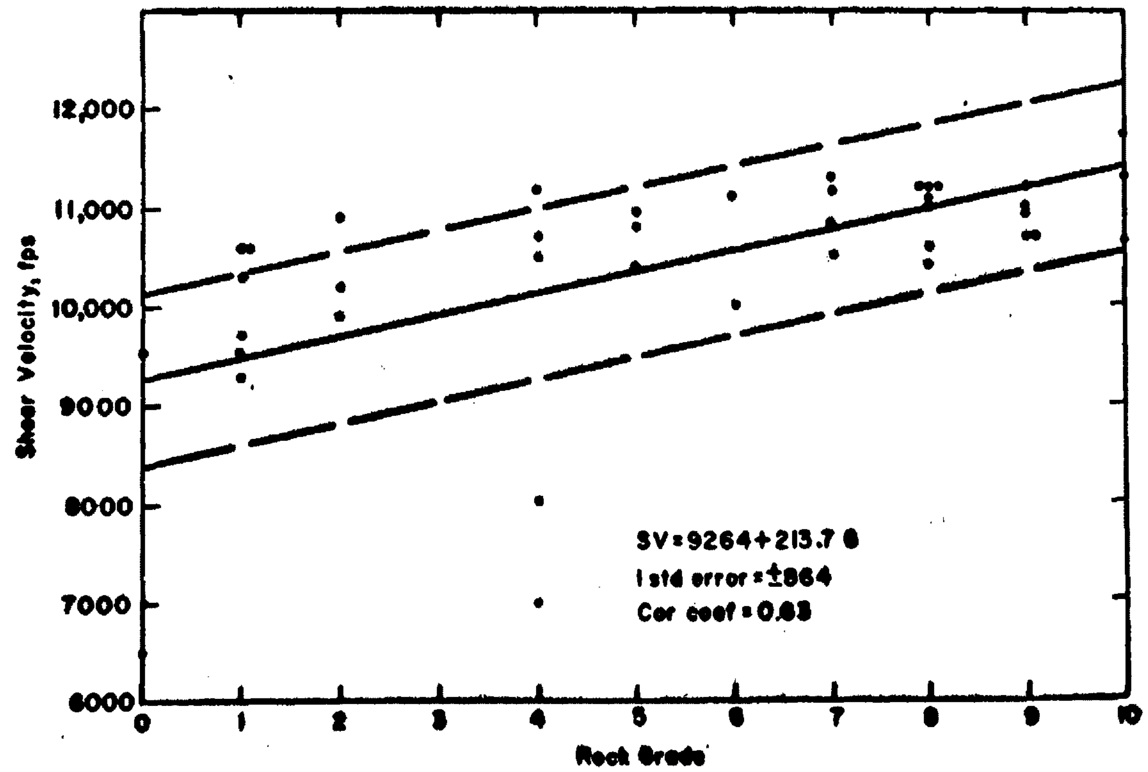


Figure 24.--Shear velocity vs. rock grade of 39 granitic samples.

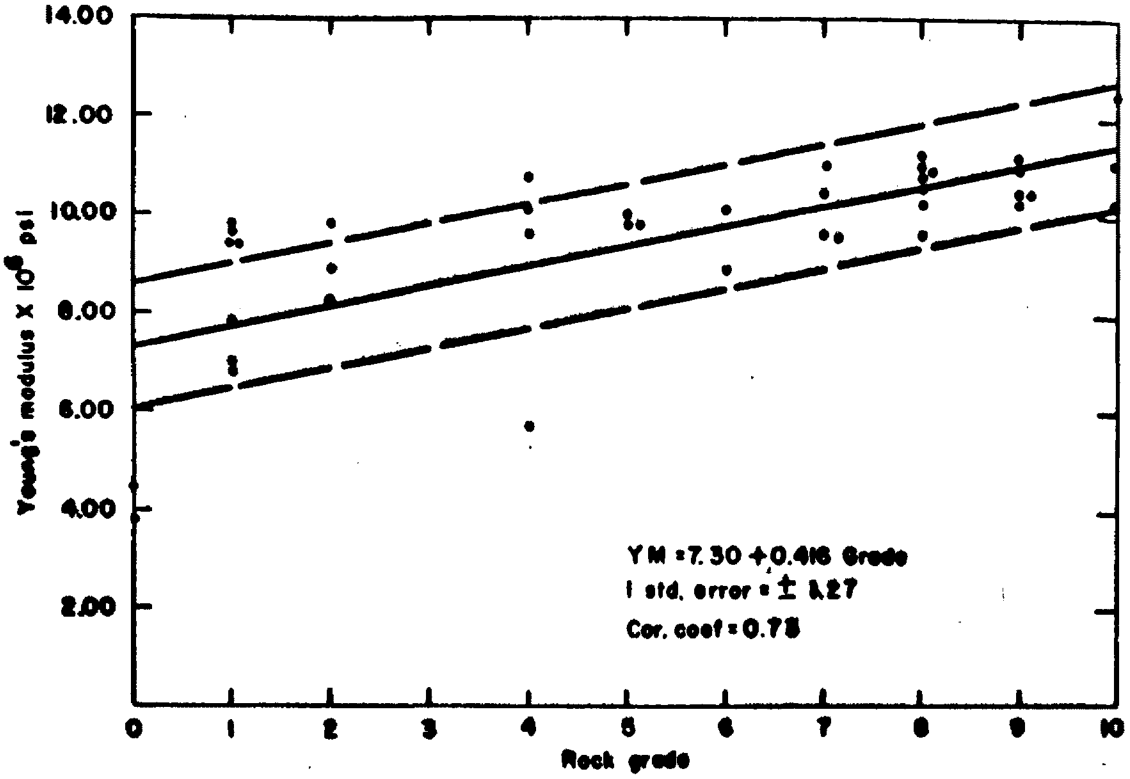


Figure 25.--Dynamic Young's modulus vs. rock grade of 39 granitic samples.

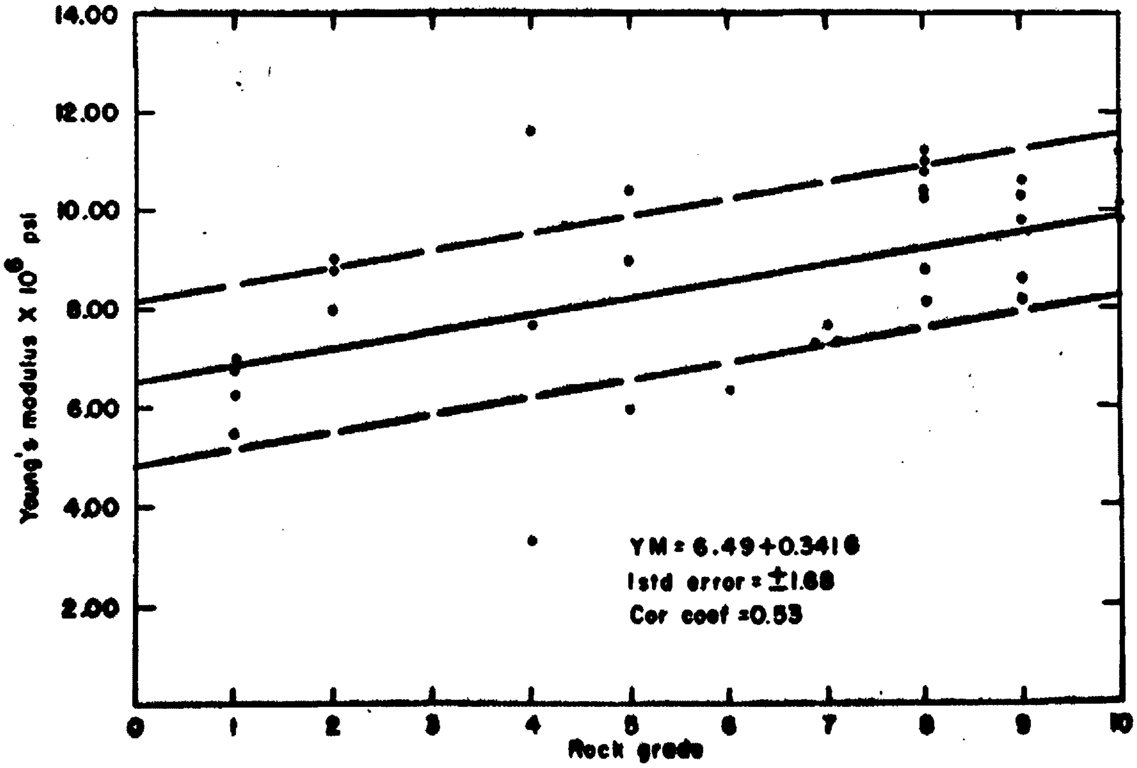


Figure 26.--Static Young's modulus vs. rock grade of 32 granitic samples.

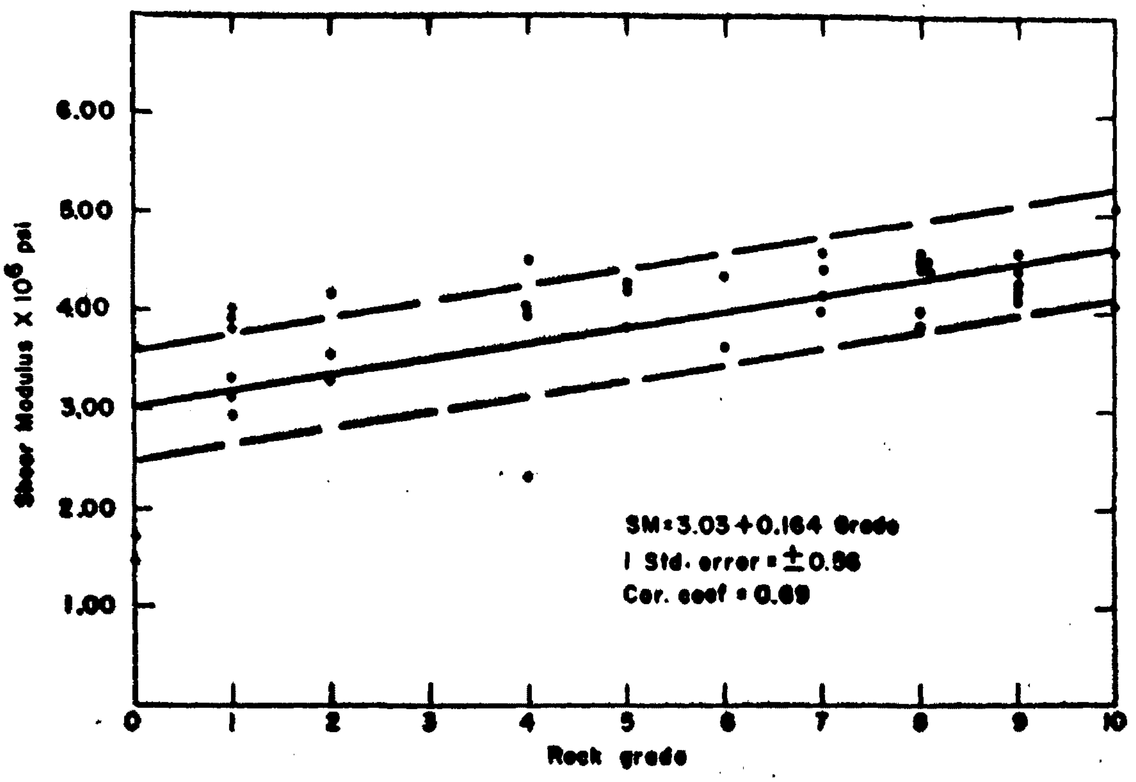


Figure 27.--Dynamic shear modulus vs. rock grade of 39 granitic samples.

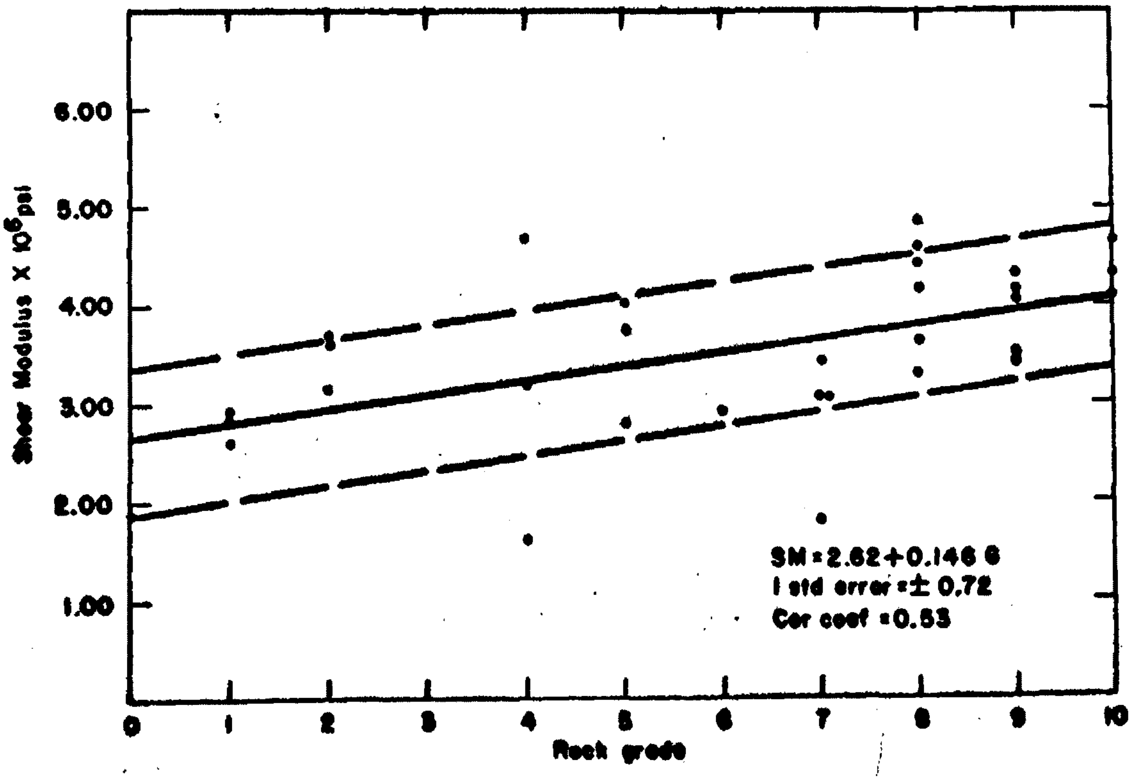


Figure 28.--Static shear modulus vs. rock grade of 32 granitic samples.

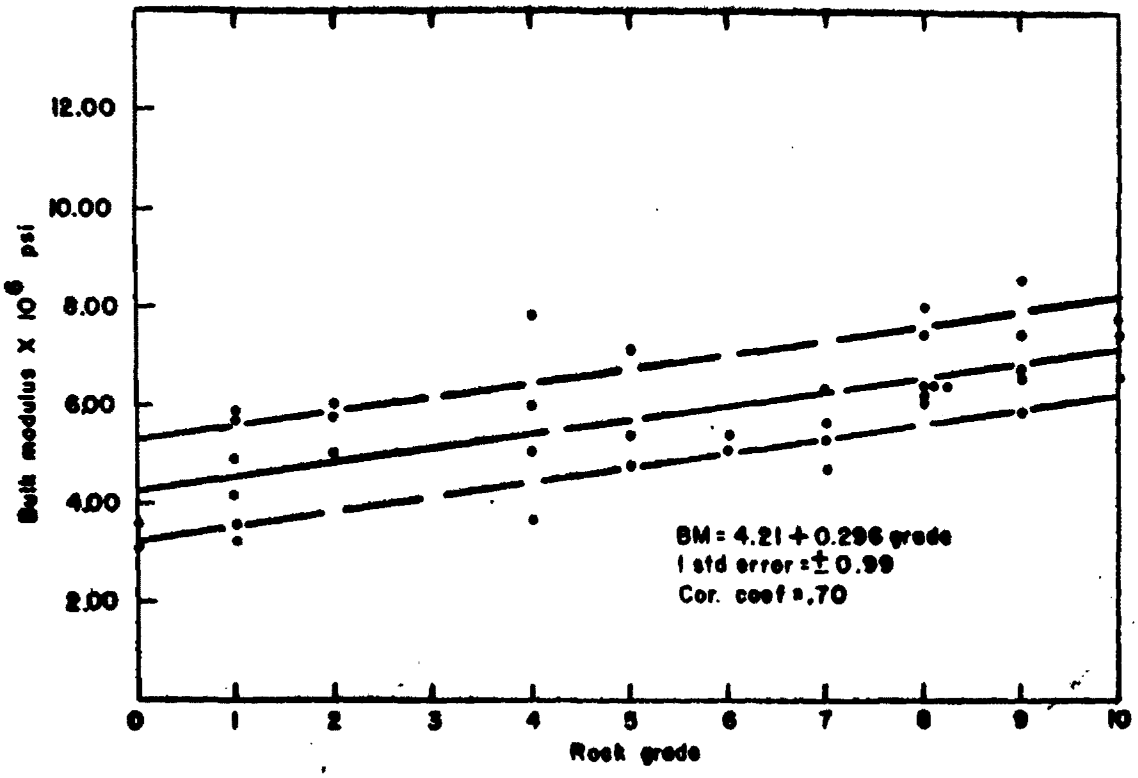


Figure 29.--Dynamic bulk modulus vs. rock grade of 39 granitic samples.

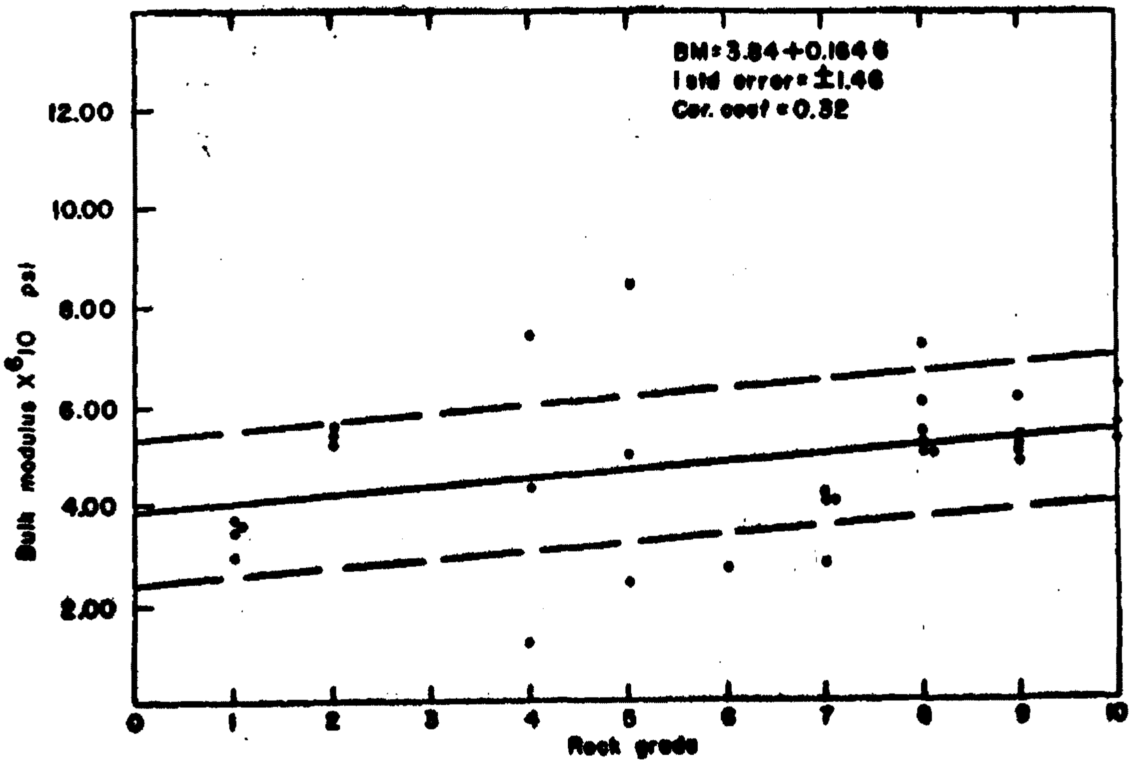


Figure 30.--Static bulk modulus vs. rock grade of 32 granitic samples.

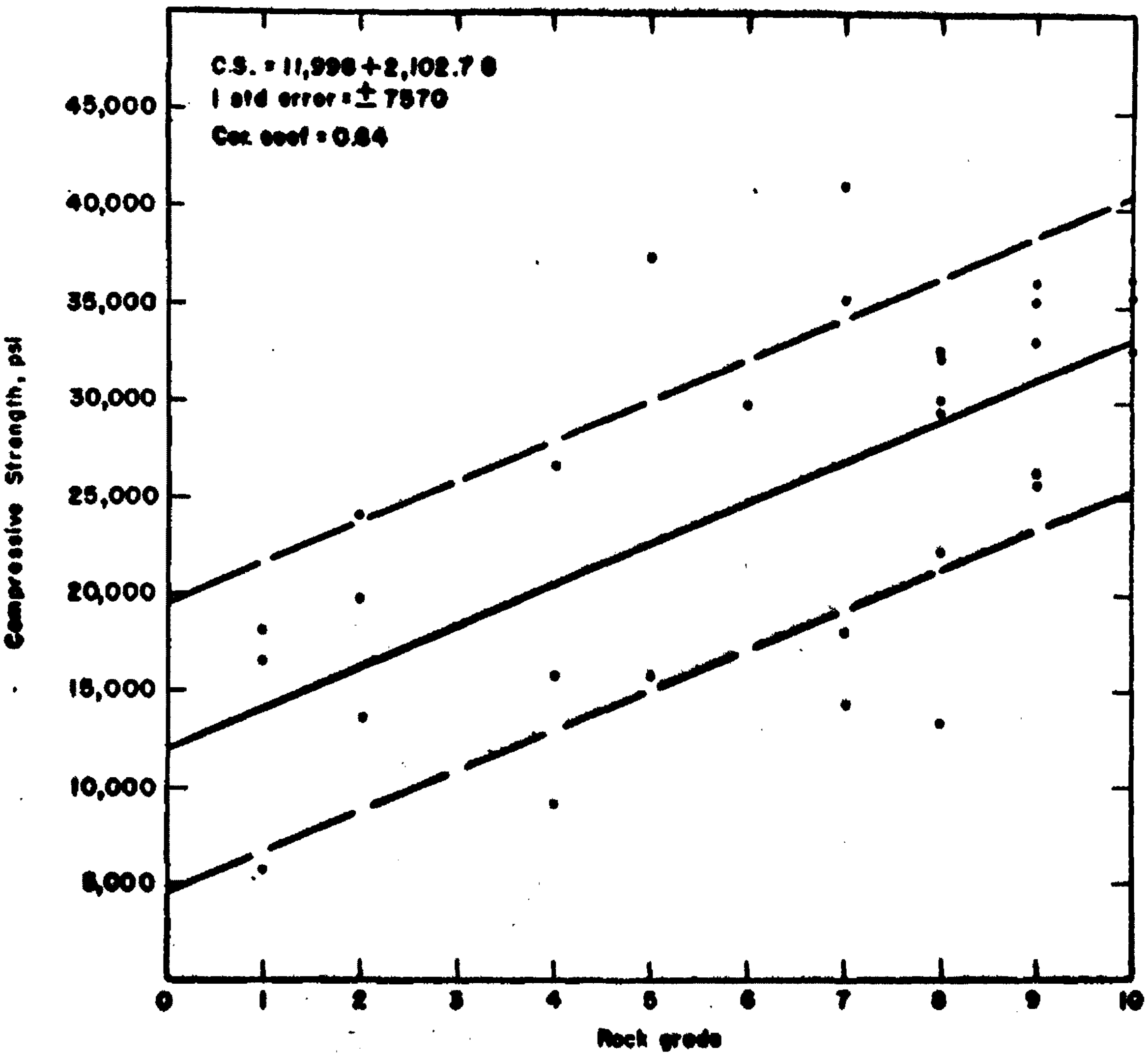


Figure 31.--Unconfined compressive strength vs. rock grade of 31 granitic samples.

Underground in-place rock conditions

The exploratory drill holes penetrated the hemisphere and adjacent communication drifts. The borings were subsequently located during underground geologic mapping. Finding the drill holes was fortuitous in that it permitted detailed examination or rock conditions in the surrounding area of the holes. Careful observation denoted the stability and competency of the rock, the need for support, the amount of timbering and steel-set spacing in unstable zones, water seepage, overbreak, major joints, faults and shear zones, and degree of weathering, alteration and hardness of the granite.

The underground rock conditions around the drill holes were carefully related to their respective core logs and rock grades. The comparison of underground and core conditions can be summarized by the following:

1) Rock penetrated by borings having assigned grades of 8 through 10 presented no construction or stability problems; the rock needed no support, and had a minimum of overbreak.

2) Rock of grades 5 through 7 needed occasional steel sets for support, was slightly to moderately blocky and tended to overbreak, especially in areas classified as grade 5.

3) Rock of grades 3 and 4 was generally poor, required support, was blocky and had a great deal of overbreak, often there were minor faults, water seeps, and zones of high joint intensity.

4) Rock of grades 0 through 2 was incompetent, needed support and generally required closely spaced sets. The rock was usually in a fault or a very strongly jointed or sheared zone, and was often associated with water seeps. The rock tended to be soft or strongly fragmented and usually could be easily removed from the wall by a geologic pick.

CONCLUSIONS

Rock is nonhomogeneous, anisotropic and imperfectly elastic. Minerals, matrix, lineations, bedding, and fractures all contribute to a non-ideal state of rock.

Study of a dacite from the Nevada Test Site showed that weathering, hydrothermal alteration, and fractures in the rock contributed to changes in its physical properties. These geologic agents reduced the unconfined compressive strength and elasticity of the dacite, and increased the porosity of the rock. Weathering changed the properties of the dacite more than hydrothermal alteration.

Computer analyses established a significant interrelation among the physical properties of dacite. Porosity is inversely related to all physical properties tested, and can be used to make reasonable predictions of rock property values.

Detailed examination of about 2,600 feet of granite core taken from borings at the Nevada Test Site showed that fractures and weathering were major factors in reducing the competency of the rock. Least-squares regression equations established significant correlations between core condition and physical properties of the granite. A Grade of Rock Table based on the interrelation of joint frequency, core loss, broken core, degree of weathering and relative hardness in the core provides a numerical means of classifying the rock into levels of competency. Comparison of in-place rock stability with core taken from the rock established a relation between core condition and in-place conditions.

APPENDIX

Table 1.--Abridged lithologic log of D.H. 1, D.H. 3, and D.H. 6, dacite porphyry, Wahmonie Flat, Nye County, Nevada

See figure 2 for drill hole locations.

Description (Color descriptions follow Munsell system)	Interval (feet)
Dacite porphyry, light gray (N-7) to white (N-9), occasionally medium light gray (N-6) and light bluish gray (5B 7/1); very severely to moderately weathered, ranges from soft plastic clay-like material to rock of intermediate hardness, vuggy, porous; severely weathered along joint planes, joint spacing 4-6 inches, joints dip 30°-40°, and 60°-90°; flow-banding at 15° from horizontal; slickensides in interval between 35 and 50 feet; core tends to slack in water; phenocrysts of feldspar, biotite, accessory magnetite and sparse quartz constitute 25-35 percent of rock, matrix is predominantly devitrified glass altering to clay------------------------------------	65
Dacite porphyry, light gray (N-7), occasionally light bluish-gray; moderately to severely weathered; intermediate hardness where not severely weathered; slightly vuggy and porous; joint spacing averages 6 inches, some joints coated with iron- and manganese-stained clay, and sparse calcite; joints dip 30°-40° and 60°-90°; flow-banding at 15° from horizontal, zones of unweathered, hard rock between 110 and 130 feet-------------------------	130

Table 1.--Abridged lithologic log of D.H. 1, D.H. 3, and D.H. 6, dacite porphyry, Wahmonie Flat, Nye County, Nevada--Continued

Description (Color descriptions follow Munsell system)	Interval (feet)
Dacite porphyry, light gray; iron stained; moderately to severely weathered; vuggy; strongly jointed with intervals of broken core; joint fillings of iron-stained clay and calcite; lost circulation at intervals below 140 feet---	160
Dacite porphyry, pale red (10R 6/2), pale red color due to oxidation of iron minerals in matrix; moderately to slightly weathered; intermediate hardness to hard; slightly vuggy and porous; joints dip 30°-40° and 60°-90°, joint spacing averages 8 inches, joints coated with iron-stained clay and calcite; flow-banding at 15°-25° from horizontal---	370
Dacite porphyry, pale red, slightly to moderately weathered; hard to intermediate hardness; joints dip 30°-40°, 60°-90°, joint spacing averages 2 feet, joints coated with iron-stained calcite and clay; flow-banding at 25° from horizontal; evidence of some hydrothermal alteration and faulting below 475 feet-----------------------------------	500

Table 1.--Abridged lithologic log of D.H. 1, D.H. 3, and D.H. 6, dacite porphyry, Wahmonie Flat, Nye County, Nevada--Continued

Description (Color descriptions follow Munsell system)	Interval (feet)
Dacite porphyry, alternating pale red and medium bluish-gray (5B 5/1), pale red dominant at top of interval grading into $\frac{1}{4}$-$\frac{1}{2}$ inch alternating color bands, medium bluish-gray dominant near base; rock oxidized only where color is pale red; hard; slightly weathered along joint planes; slight hydrothermal alteration in medium bluish-gray rock increasing below 550 feet; joints dip 60°-90°, joint spacing ranges between 8-12 inches; shear zone between 570 and 600 feet, flow-banding at 25°-45° from horizontal	650
Dacite porphyry, medium bluish-gray (5B 5/1); unweathered to slightly weathered along joints; hard; nonoxidized; rock has been subjected to silica-bearing hydrothermal solutions, which locally have deposited opal and formed reaction products of calcite, chlorite and epidote; groundmass is grayish-blue-green (5BG 5/2) where chloritized; core is solid and comes from core barrel in long unbroken lengths; joints dip 60°-90°, spacing averages 2 feet, joints are tight and sealed with calcite; shear zone between 760 and 790 feet; flow-banding at 25°-45° from horizontal	920
Dacite porphyry, same as above, shear and fault zone	1,000

Table 7.--Lithologic log of granite exploratory core, Climax stock, Nye County, Nevada

Nevada State (central) coordinates: N. 901;010.22; E. 677,685.28

Ground elevation: 5,014.4 feet above sea level

Description	Interval (feet)	Recovery (percent)
No core--	0-59.5	
Quartz monzonite porphyry; light gray and heavily iron stained; fine grained; contains quartz, feldspar, and biotite (3-5 percent) crystals, and feldspar phenocrysts as much as 1 inch in length; severely weathered; heavy kaolinization of feldspars, small broken pieces of rock are turning to clay; incompetent; strongly jointed and broken; joints are mostly open; joint fillings are iron oxide, clay and calcite------------------------------	59.5-74.5	93.3
Shear and Fault Zone. Quartz monzonite porphyry; very severely weathered; completely incompetent; entire interval is broken into pebble-sized fragments; very heavy kaolinization of feldspars; the rock in this interval is breaking down into clay; slickensides are on joint and fracture surfaces throughout the interval; drill hole was caving in this area-------------------------------------	74.5-95.0	58.5

Table 7.--Lithologic log of granite exploratory core, Climax stock, Nye County, Nevada--Continued

Description	Interval (feet)	Recovery (percent)
Shear Zone. Quartz monzonite porphyry; light gray and bleached; coarse grained; contains quartz, feldspar, and biotite (3-5 percent) crystals, and feldspar phenocrysts as much as 1 inch in length; severely weathered; heavy kaolinization of feldspars; incompetent; strongly jointed and broken; joints are mostly open; joint fillings are clay, calcite, and iron oxide------------------------------------	95.0-107.0	91.7
Shear and Fault Zone. Quartz monzonite porphyry; light gray and iron stained; very severely weathered; completely incompetent; very strongly jointed and broken into pebble-sized fragments throughout most the interval; heavy kaolinization of feldspars; most rock fragments are breaking down into clay--------	107.0-120.2	45.4
Shear Zone. Quartz monzonite porphyry; light gray; medium grained; contains quartz, feldspar, and biotite (3-5 percent) crystals, and feldspar phenocrysts as much as ½ inch in length; severely weathered; heavy kaolinization of feldspars; rock fragments are breaking down into clay; incompetent; strongly jointed		

Table 7.--Lithologic log of granite exploratory core, Climax stock, Nye County, Nevada--Continued

Description	Interval (feet)	Recovery (percent)
and broken joints are mostly open; joint fillings are thick clay, calcite, iron oxide, and manganese; a few slickensides occur on joint surfaces----------------------------------	120.2-141.0	70.7
Shear and Fault Zone. Quartz monzonite porphyry; very severely weathered; completely incompetent; entire interval is broken into pebble-sized fragments; there is clay, calcite, and iron oxide on rock fragments and joint surfaces; heavy kaolinization of feldspars; rock fragments are breaking down into clay; slickensides occur on joint surfaces-----	141.0-156.3	42.5
Shear Zone. Quartz monzonite porphyry; light gray; mostly severely weathered; moderately weathered in short intervals; generally incompetent; short intervals of moderately firm rock between 157 and 160 ft. and 168 to 169 ft.; joints are mostly open; joint fillings are clay, iron oxide, and calcite--	156.3-175.0	70.6

Table 7.--Lithologic log of granite exploratory core, Climax stock, Nye County, Nevada--Continued

Description	Interval (feet)	Recovery (percent)
Quartz monzonite porphyry; light bluish-gray; contains quartz, feldspar, and biotite (3-5 percent) crystals; slightly to moderately weathered; moderate kaolinization of feldspar especially along joint surfaces; this interval seems to be less intensely weathered; moderately firm and competent; rock tends to break into pieces between 2 and 12 inches in length; strongly jointed, joints are mostly open, joint fillings are clay, calcite, and iron oxide, some joints are sealed with pyrite---------------------------	175.0-201.0	55.8
Quartz monzonite porphyry; bluish gray; fine textured; contains quartz, feldspar, and biotite crystals, and feldspar phenocrysts as much as 1 inch in length; unweathered to slightly weathered; slight kaolinization of feldspars along joint surfaces; rock seems to be out of weathered zone; firm and competent; slightly jointed, joints are mostly open, joint fillings are calcite and some fresh pyrite----------------------------------	201.0-220.0	99.5

Table 7.--Lithologic log of granite exploratory core, Climax stock, Nye County, Nevada--Continued

Description	Interval (feet)	Recovery (percent)
Same as above, except moderately weathered; moderately jointed---------------------------	220.0-229.0	75.6
Shear and Fault Zone. Quartz monzonite porphyry; very severely weathered; completely incompetent; interval is broken into pebble- to sand-sized fragments; this interval contains mylonite and clay; slickensides occur on fragments surfaces-----------------------	229.0-235.4	70.3
Quartz monzonite porphyry; bluish gray; medium grained; contains quartz, feldspar and biotite (3-5 percent) crystals, and feldspar phenocrysts as much as 1 inch in length; unweathered to slightly weathered; very firm; slightly jointed; joints are mostly open; joint fillings are calcite and some fresh pyrite; some joints are sealed with pyrite; core is broken in the interval from 256.5 to 257.0 ft. into pebble-sized fragments----------------------------	235.4-260.5	94.0
Shear Zone. Quartz monzonite porphyry; light bluish gray; fine grained; contains quartz, feldspar, and biotite (3-5 percent) crystals; slightly weathered in solid core to severely		

Table 7.--Lithologic log of granite exploratory core, Climax stock, Nye County, Nevada--Continued

Description	Interval (feet)	Recovery (percent)
weathered in broken intervals; heavy kaolinization of feldspars in broken zone; there is a short section of clay and mylonite as much as 6 inches in length; generally incompetent; strongly jointed; two-thirds of the interval is broken into pieces 3 inches and less in length; joints are mostly open; joint fillings are clay, calcite, and iron oxide; this interval seems to be a shear zone in good competent rock--	260.5-279.4	71.4
Quartz monzonite porphyry; light bluish-gray; fine grained; contains quartz, feldspar, and biotite (3 percent) crystals, and sparse feldspar phenocrysts as much as ½ inch in length; slightly weathered in solid rock to severely weathered in broken rock; moderately firm; stongly jointed; about 25 percent of this interval is broken into pieces 3 inches and less in length; joints are mostly open; joint fillings are clay, calcite, iron oxide, and sparse fresh pyrite; this interval seems to be a shear zone in good competent rock, although less intensely sheared than above-----	279.4-327.0	73.5

Table 7.--Lithologic log of granite exploratory core, Climax stock, Nye County, Nevada--Continued

Description	Interval (feet)	Recovery (percent)
Fault. Quartz monzonite porphyry; light bluish-gray; very severely weathered; completely incompetent; interval is composed of clay, mylonite and broken core---------------------	327.0-331.0	87.5
Quartz monzonite porphyry; light bluish-gray; medium grained; contains quartz, feldspar, and biotite (3 percent) crystals, and feldspar phenocrysts as much as 2 inches in length; slightly weathered in solid core; moderately weathered in broken rock; feldspars are kaolinized in broken rock; firm in solid core; incompetent in broken rock; slightly jointed; 10 percent of this interval is broken into pebble-sized fragments; joints are both open and sealed; joint fillings are calcite, some clay, fresh pyrite, and sparse iron oxide. Core is broken in the intervals from 347.0 to 350.0; and 345.5 and 355.0 ft. There is mylonite and clay in the interval from 347 to 350 ft. indicating a possible small shear------------	331.0-369.6	94.0

Table 7.--Lithologic log of granite exploratory core, Climax stock, Nye County Nevada--Continued

Description	Interval (feet)	Recovery (percent)
Quartz monzonite porphyry; light bluish-gray; medium grained; contains quartz, feldspar, and biotite (3 percent) crystals, and feldspar phenocrysts as much as 1 inch in length; slightly weathered in solid core; moderately weathered in broken rock; feldspars are kaolinized in broken rock; firm in solid core; imcompetent in broken rock; moderately jointed; joints are mostly open; joint fillings are mostly calcite; core is broken into pieces 2 inches or less in length in the interval from 448.6 to 453.3 ft.--------------------------	435.3-454.3	80.0
Quartz monzonite porphyry; light bluish-gray; medium grained; contains quartz, feldspar and biotite (3 percent) crystals, and sparse feldspar phenocrysts as much as 1 inch in length; unweathered to slightly weathered; very firm; slightly jointed; jointing tends to increase below 470 ft. unbroken core as much as 4.5 ft. in length; joints are both open and tight; joint fillings are calcite and pyrite; tight joints are sealed with pyrite----------------	454.3-484.4	90.4

Table 7.--Lithologic log of granite exploratory core, Climax stock, Nye County Nevada--Continued

Description	Interval (feet)	Recovery (percent)
Quartz monzonite porphyry; light bluish-gray; medium grained; contains quartz, feldspar, and biotite (3 percent) crystals, and feldspar phenocrysts as much as 2 inches in length; slightly weathered; firm; moderately jointed; joints are mostly open; joint fillings are calcite and sparse pyrite--------------------	484.4-499.4	92.0
Shear Zone. Quartz monzonite porphyry; light bluish-gray; medium grained; contains quartz, feldspar, and biotite (3 percent) crystals, and sparse feldspar phenocrysts as much as 2 inches in length; moderately weathered in solid core; and strongly weathered in broken rock; weathering or alteration of core gives rock a coarse texture; strongly jointed; 25 percent of this interval is crushed rock, mylonite and clay; joints are open, joint fillings are mostly calcite and iron oxide; the crushed rock is heavily iron stained; this interval seems to have been sheared with some movement--------------------------	499.4-507.0	61.8

Table 7.--Lithologic log of granite exploratory core, Climax stock, Nye County Nevada--Continued

Description	Interval (feet)	Recovery (percent)
Quartz monzonite porphyry; light bluish-gray; medium grained; contains quartz, feldspar, and biotite (3 percent) crystals, and sparse feldspar phenocrysts as much as 1 inch in length; slightly weathered; very firm; slightly jointed; joints are mostly sealed; joint fillings in sealed joints are pyrite and in open joints are calcite----------------------	507.0-513.1	98.4
Quartz monzonite porphyry; light bluish-gray; medium grained; contains quartz, feldspar, and biotite (3 percent) crystals, and sparse feldspar phenocrysts as much as 2 inches in length; generally moderately weathered; severely weathered in broken rock; moderately weathered; severely weathered in broken rock; moderately firm; moderately jointed, 10 percent of this interval is broken; joints are mostly open; joint fillings are mostly calcite, iron oxide, and sparse clay. This interval has undergone some shearing---------	513.1-552.9	84.2

Table 7.--Lithologic log of granite exploratory core, Climax stock, Nye County Nevada--Continued

Description	Interval (feet)	Recovery (percent)
Quartz monzonite porphyry; light bluish-gray; medium to fine grained; contains quartz, feldspar, and biotite (3 percent) crystals, and sparse feldspar phenocrysts as much as 1 inch in length; unweathered; very firm; slightly jointed, joints are mostly sealed; joint fillings are mostly silica, feldspar, and pyrite in sealed joints and calcite in open joints; unbroken core are as much as 5 feet in length------------------------------------	552.9-585.9	85.7
Fault. Quartz monzonite porphyry; light-bluish gray; this interval is composed of broken rock, mylonite, and clay; completely incompetent; there is calcite, iron oxide, and clay on fragment surfaces------------------------	585.9-594.1	85.3
Quartz monzonite porphyry; light bluish-gray; medium to fine grained; contains quartz, feldspar, and biotite (3 percent) crystals, and sparse feldspar as much as 1 inch in length; unweathered to slightly weathered; very firm in solid core; slightly jointed; joints are both open and sealed with quartz, feldspar, and pyrite; this interval has been effected by some slight shearing---------------------	594.1-656.9	81.2

Table 7.--Lithologic log of granite exploratory core, Climax stock, Nye County, Nevada--Continued

Joint Intensity Code

Descriptive terms	Approximate numerical value (joints/foot)
Few joints	Less than 1
Slightly jointed	1 to 2.9
Moderately jointed	3 to 4.9
Strongly jointed	5 to 6.9
Very strongly jointed	More than 7

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