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PETROGRAPHIC AND PHYSICAL PROPERTIES TECHNIQUES FOR STUDY OF FOUNDATION ROCK MORROW POINT DAMSITE

Determining petrographic characteristics of the rock and their relationship to modulus of elasticity.

S. R. Rubenstein
Engineering and Research Center
Bureau of Reclamation

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16. ABSTRACT
During the foundation investigation of schists and gneisses at Morrow Point damsite, the rock (Nx cores) was petrographically described and classified for structural tests. Petrographic and physical tests of the core were grouped to give an overall picture of the foundation. Methods are described for determining the petrographic characteristics such as articulation, mineral composition, and microstructure of the rock. Articulation and texture of the grains were determined on the basis of microscope examination for evaluation of bond strength. Composition of the rock was determined by modal analysis (by a method of intercept distances) and the rocks were grouped according to minerals present. Oriented microstructures in foliated rocks were determined by the photometer method for analysis of structure. The relationship between elasticity and the texture composition, and structure was compared. The relationship between absorption and seismic wave velocity was examined. Physical properties by means of laboratory and seismic methods were measured for individual rock types.

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INTRODUCTION

In the investigation of foundation rocks at Morrow Point Damsite, Colorado,[1] rock cores were petrographically classified and logged. Certain physical tests were also performed and related to engineering properties of design.

Morrow Point damsite is located on the Gunnison River, upstream from the confluence with Cimarron Creek. Geologically, the Gunnison River cuts through Pre-Cambrian gneisses, schists, and pegmatite at the damsite.

Because the dam will be a thin arch, double-curvature designed dam, extensive geologic investigations were undertaken. In addition to the geological studies, structural properties of the rock were determined. This paper is concerned with the description of some of the petrographic techniques which are used in the investigation of geological conditions in rock foundations and the manner in which such information can be presented in engineering terms.

Twenty-nine representative samples of Nx (2-1/8 inches) core from exploration drill holes and tunnels were examined. For the petrographic examination, each piece was selected so that its location in the drill hole was as close as possible to another core piece which was tested for compressive strength, elasticity, and other properties by the Rock Mechanics and Structures Unit of the Division of Research.

Microscopic examination was performed for determination of composition, internal structure, texture, secondary minerals, and microcracks. Modal analysis was used to provide a quantitative composition of the rock. The photometer technique provide a method to determine the lineation and microstructure of the rock by the orientation of the quartz grains.

X-ray diffraction analysis for determination of fine-grained minerals was made as well as spectrographic analysis for semiquantitative determination of elements. Clay staining tests for qualitative determination of clay were done when necessary. Determinations of porosity, absorption, and bulk specific gravity (specific gravity with the permeable voids filled with water) by the immersion method were made to obtain these physical properties of the rock. Elasticity and unconfined compressive strength tests were performed.[2]

[1] Numbers refer to references at end of paper.

CONCLUSIONS

1. The rock grouping of the cores by hammer hardness from soft, moderately hard, to hard showed fairly good correlation with elasticity. Those which had a good "ring" were harder than those with a duller "ring." The soft group had a lower elasticity.

   a. The petrographic identification and classification was a good method for determining the characteristics that effect the engineering properties of the rock. Trends were obtained between texture, structure, composition, and strength and elasticity. Strength increased as the amount of quartz increased and mica decreased. The increase in strength appears to result from greater locking of the crystals as the transition from parallel to anhedral (shapeless crystals) to euhedral (bounded by its own crystal faces) fabric occurs.

   b. Modal compositional analysis by the thin section method gave more accurate mineral percentages as compared to visual estimation. The mineral percentages then can be used in the identification of the rock. The data can also be used in the correlation with structural properties. There was a decrease in strength when the quantity of mica was greater than 40 to 50 percent.

   c. The anistropy of the biotite schists caused notable differences in strength in core samples tested along their isotropic planes of weakness.

2. Absorption data was related to the elasticity of the rock. The absorption was low and when compared to elasticity showed the lower the absorption the higher the elasticity.

3. Photomicrographs can be an aid to determining texture and articulation in the classification of rock types. Stereo photomicrographs can be an aid to explain surface roughness.

APPLICATION

Petrographic techniques such as classification, modal analysis, petrofabric study, chemical analysis, and hardness tests with strength and modulus of elasticity tests provided a good method for determining the behavior of the foundation rock at Morrow Point site.

TEST METHODS

Chemical Analysis and Correlation

It was important in the investigation of the foundation to determine the petrogenesis of the rock for excavation and structural purposes. The chemical compounds were obtained from the thin section mineral analysis of the metamorphic rocks. Certain groups of compounds (SiO_2 and Al_2O_3) were then compared with a chemical analysis of average sedimentary rock types (Table 1).

Rock Groupings by Hardness

In order to resolve the complex data into usable engineering units, five different rock types were derived based on approximate hammer hardness, foliation, and grain size grouped as follows:

Group I	Biotite schist
Group II	Mica schist + mica augen schist
Group III	Quartz-mica schist
Group IV	Quartzite
Group V	Pegmatite

Rock Classification by Texture

The petrographic analysis is a rapid method for investigating the characteristics of foundation materials. The petrographic description and classification of foundation rock also serves as a guide for correlation of the strength and elastic properties. It has been found that rocks with almost identical geological classification (name, age, formation) may vary widely in their physical characteristics. Therefore, designs should be based on physical and elastic properties of foundation rocks that have actually been tested or compared with a petrographically similar type of rock whose characteristics correlate closely with the one being considered.

Under the microscope, the rocks were classified on the basis of articulation (manner in which adjacent mineral grains join) and texture. The grain boundaries are either sutured, sinuous, or smooth to planer. The textures vary from schistose and banded to granular and are interlocking rather than cemented compared to sedimentary rocks. The articulation varies from very poorly locked to poorly locked as shown in the following table:

TEXTURAL CLASSIFICATION

Group	Rock	Articulation	Textur
I	Biotite schist	Very poorly interlocked	Schistos
II	Mica schist and quartz-mica schist	Very poorly interlocked	Schistos to bandec
III	Micaceous quartzite	Very poorly to poorly interlocked	Banded granula
IV	Quartzite	Poorly interlocked	Granular
V	Pegmatite	Poorly interlocked	Granular

Grain size was measured with the aid of a calibrate eyepiece fitted to the microscope. The thin section w randomly scanned and measurements made. This w compared to a representative thin section in which 3C grains were measured.

Macrostructure (Foliation and Fractures)

The angle of foliation with the vertical axis of the cor as measured with a protractor varied from 30° to 90° The amount of foliation estimated varied fror well-foliated to nonfoliated. The foliation wa compared with the strength (Figure 4) and elasticity

For correlation purposes, the type and frequency o fractures in the rock cores from DH 31 and 12 wer noted. A relatively small number of fractures (13 to 3 in 250 feet of core) were present, they were parallel tc the foliation, and generally they occurred more thar 10 feet apart (see log of drill holes—Appendix).

Modal Analysis (Composition)

A modal analysis for the determination of the composition of the rock for classification and description was performed. This was done by a modified Rosiwal (1898)[4] method, which is a technique of determining volume percentage of minerals by measurements in thin section. Instead of measuring every grain, a method of intercept distances (Chayes 1949)[5] for making rapid estimates of mineral composition from thin sections and slabs (Plafker 1956)[6] was used, Table 2A.

A statistical analysis was made to determine the limits of error between the thin section and slab results, Table 2B.

Photometer Method of Petrofabric Study

Orientation of the quartz grains was determined by the photometer method, which consists of measuring by means of an attached photometer the variation in intensity of monochromatic light passed through individual grains of a thin section on the stage of a petrographic microscope, with gypsum plate inserted and nicols crossed during 360° rotation of the microscope stage. A light intensity minimum occurs when the trend of the optic axis of the quartz grains is parallel with the slow direction of vibration of the gypsum plates. Petrofabric analysis by the photometer method[7] was performed to investigate rock foliation, deformation, as well as genesis of the rocks, Table 3.

Specific Gravity and Absorption

Bulk specific gravity and absorption were determined by the suspension method described in the Concrete Manual (1963).[8] Using absorption as an index of alterability, absorption was compared to elasticity.

Photomicrographs were taken to illustrate the texture of the rock. The schistose texture was seen as parallel alinement of the elongated mica flakes (Appendix). The banded texture showed alternating layers of light and dark minerals, while the granular texture was indicated by the grains of equal size without preferred orientation. Granular texture was also indicated in the granite pegmatite.

Compressive Strength and Elasticity

Compressive strength, as used in this report, is the ultimate unit load a cylinder will support in the axial direction when it is unconfined laterally. It is a particular case of triaxial testing with a zero lateral stress.

Static elastic properties are determined by loading the cores axially in compression and measuring longitudinal and lateral strains. These strains are measured for loads applied continuously up to approximately one-third of the ultimate compressive strength (Table 4).

Comparison of Petrographic and Structural Properties

Application and development of the foundation geology was directed at detecting, delineating, and three dimensionally defining natural suites or patterns in the foundation rock.

These rock types were developed from megascopic field classification and refined by petrographic and laboratory methods (Figures 1, 2, and 3).

In order to resolve the detailed and complex foundation data into useable field and construction units, five different rock types were distinguished (I to V).

Physical properties by means of laboratory and seismic methods were then developed for individual rock types. These properties were evaluated and applied to natural suites which existed in the foundation rock (Seismic Measurements of Rock Elasticity—Appendix). Emphasis was placed on comparative analysis of quantitative data in order to produce for the designing engineer localized and composite indications of the engineering properties and anticipated behavior of rock foundations.

The rock groups based on hardness (soft to hard) were compared with elasticity values of samples from Drill Holes 7 and 12 and correlation was good, Table 5.

Group I (soft) had the lowest elasticity values.

Elasticity was affected by variations in (a) interlocking of constituent grains, (b) direction of foliation of the rock, and (c) amount of compressible minerals. The articulation or locking of the grains of the schist, gneiss, and quartzite was compared to elasticity, Table 6A, Figure 5. The texture ranged from very poorly (biotite schist) to poorly locked (quartzite). The very poorly locked samples had the low elasticity values. This compared favorably with a textural and mineralogical classification of metamorphic rocks from other Bureau projects, Table 6B. Variations in the direction of foliation ranged from 0° to 90°. The rock with the low angle (0° to 35° from the vertical) of foliation had the low elasticity, Table 7. The results of the petrofabric analysis indicated that the rocks with preferred orientation of quartz grains had the lower elasticity values in the samples (mica quartz schist—quartz mica schist) tested. Mica was the chief compressible mineral. The results of the mineral analysis indicated that the percentage of mica, which ranged from 10 to 90 percent, varied with percent quartz and inversely with elasticity. Table 8, Figure 6, shows a comparison of quartz and mica with elasticity.

The laboratory absorptions in general were low and ranged from 0.06 to 2.4 percent. This indicates fairly uniform rock. The low values were due to the very small amount of pores and microcracks present.

Although iron stained microcracks are evident in these rocks, apparently they are tight. For the purpose of correlation, values from 0.06 to 0.9 percent were used, as no elasticity data were available for values over 0.9 percent, Table 9, Figure 7. The mica schists and biotite schists generally had the high absorptions.

It is known that seismic velocities are effected by moisture content. Absorption percentages were compared with seismic values from a 153-foot drill hole (DH 31) and generally showed the rocks with the lower absorptions had the higher elasticity value.

Bulk specific gravity ranged from 2.68 to 2.83 for the schist. The pegmatite ranged from 2.62 to 2.69. The higher specific gravity was due to the higher percentage of heavier mica in the rock. The average (2.73) consisted of rocks containing 60 percent quartz. The higher specific gravities had the lower elasticity values.

Stereo photomicrographs were taken to show surface roughness after shear tests. It was found that biotite, if it is not alined in the plane of foliation, presented a rough place in the surface (asperites) (Appendix).

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[2] U.S, Bureau of Reclamation, *Materials Laborator Procedures Manual,* Denver, Colorado, (1957)

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[8] U.S. Bureau of Reclamation, *Concrete Manual* Seventh Edition, Denver, Colorado, (1963)

Table 1

CHEMICAL COMPOSITION

	Orthoquartzite	Graywacke	Schist*
SiO_2	92.3	63.9	71.06
TiO_2	0.0	0.4	0.60
Al_2O_3	1.4	14.1	13.23
Fe_2O_3	0.2	3.5	1.17
FeO	0.3	1.6	3.57
MnO	–	–	0.13
MgO	0.1	1.7	0.95
CaO	3.0	2.6	1.48
Na_2O	0.1	1.5	3.98
K_2O	0.1	4.0	2.74
H_2O+0	0.2	3.5	0.32
H_2O			1.16
P_2O_5	–	0.1	0.16
CO_2	2.3	1.9	–
ZrO_2	–	–	0.02

*River Portal mica schist (GC 58), three-fourths of a mile south of Nyswanver Spring, Vernal Mesa, Montrose County, Colorado, Analyst George Steiger, (J. F. Hunter—Pre-Cambrian Rocks of Gunnison River, Colorado, USGS Bulletin 777, 1925)

As evidence favoring sedimentary origin, the mineralogical analysis from the table of average modes shows that the relative quantities of alumina for the muscovite-biotite schist are significantly high (12 percent, based on 38.5 percent of the muscovite is aluminum). Also as shown by this table, the minor quantities of sodium and potassium (present in feldspar and mica) tend to relate to sedimentary origin.

Table 2A

MODAL ANALYSIS OF PRE-CAMBRIAN ROCKS

Minerals	1	2	3
Quartz	42.3	64.2	73.1
K feldspar	2.3	6.0	5.2
Plagioclase	–	–	–
Biotite	20.3	16.6	12.5
Muscovite	31.4	11.2	9.0
Sillimanite	1.0	Trace	–
Clay	2.7	2.0	–
Zircon	Trace	Trace	–
Garnet	Trace	Trace	–
Grain size (mm)	4.2	2.7	2.2

1. Biotite schist
2. Mica quartz and mica augen schist
3. Quartz mica schist

Table 2B

RESULTS OF COMBINED ROCK AND
THIN SECTION ANALYSIS OF SPECIMEN

	Limits (percent) *1	**2	*3	Mean	Standard deviation (percent)
Quartz, Feldspar	69.5	66.1	68.0	67.8	1.39
Biotite	25.0	28.5	22.0	25.3	2.54
Sillimanite, Muscovite	5.5	5.2	10.0	6.9	2.17
Others					

*Rock
**Thin section

Table 3

PREFERRED ORIENTATION OF QUARTZ IN FOUNDATION ROCK
MORROW POINT DAMSITE

No.	Drill hole	Depth	Rock	Grain orientation
P-7081	9	142.0	Quartz-mica schist	Mica (P)* Quartz (R)**
P-7116	26	42.3	Quartz-mica augen schist	Mica (P), Quartz 45^{o}
P-7121	12	25.8	Mica-quartz schist	Mica (P), Quartz (P)
P-7117	26	52.6	Quartz-mica schist	Mica (P), Quartz (R)
P-7119	31	26.0	Quartz-mica schist	Mica (P), Quartz (R)
P-7080	7	177.0	Quartz-mica schist	Mica (P), Quartz (R)

*(P) Parallel to the lineation
**(R) Random

Note: Muscovite-biotite schist is both linear and foliated with mica and quartz parallel to foliation.

Table 4

PHYSICAL PROPERTIES

Group	Rock type	Drill hole	Depth (feet)	Specific gravity	Compressive strength psi	Elasticity*
I	Biotite	7	103.0	2.78	4,350	0.65
	schist	7	97.0	2.81	4,350	–
II	Mica schist	26	96.0	–	3,030	–
		31	132.0	–	3,530	–
		9	92.1	–	4,850	–
		Tun.	–	–	5,300	–
		12	25.8	2.70	7,980	2.33
III	Quartz-mica schist	12	164.0	–	8,320	1.52
		26	42.3	–	12,190	6.06
		26	52.6	2.70	10,860	3.23
		7	177.0	2.71	14,400	2.75
		31	26.0	2.70	14,600	4.67
		9	142.5	2.68	14,890	–
		12	92.1	–	15,880	2.40
IV	Quartzite	7	62.7	–	21,210	6.49
		32	117.2	–	23,630	7.49
		7	135.0	–	25,860	4.48
		12	183.0	–	28,900	5.68
	Hornblende-schist	12	96.0	–	12,440	–
V	Granite-pegmatite	32	27.0	–	8,520	2.81
		10	103.7	–	13,140	–

*E x 10^6 psi

Table 5

STATIC LABORATORY TESTS
Drill Holes 7 and 12*

Group	Rock	Elasticity x 10^6 psi
I	Soft	0.65
II	Moderately hard	1.3–2.2
III, V	Moderately hard to hard	2.4–6.4
IV	Very hard	–

*Morrow Point Dam and Powerplant Investigations, Bureau of Reclamation, October 1965 (Appendix C, Table 6)

Table 6A

ARTICULATION COMPARED TO ELASTICITY

Gram size (mm)	Texture	Elasticity x 10^6 psi
0.5 –0.10	Very poorly locked (parallel)	0.76–1.64
		1.30–2.18
1.38–4.01	Very poorly to poorly locked	2.22–6.49
0.55	Poorly locked	4.48–7.90

Table 6B

TEXTURAL AND MINERALOGICAL CLASSIFICATION OF ROCKS VS PHYSICAL PROPERTIES

Structure:	Foliated	Banded	Granular
Texture:	Very poorly interlocked	Very poorly to poorly interlocked	Poorly interlocked
Rock type:	Schist	Gneiss	Quartzite Amphibolite
Minerals (strong/weak):	Quartz/ Mica** chlorite	Quartz + K, Na Feldspar/ Biotite	Quartz and Na Feldspar/ Hornblende
Comp. strength:* (Porous–5 – 10 x 10^3) (Very porous–1 – 5 x 10^3)	1 – 11 x 10^3	9 – 15 x 10^3	21 – 40 x 10^3
Percent porosity:	0.40 – 1.1 –11.0	0.22 – 0.49	0.23 – 0.48

*Structural data from Bureau of Reclamation damsites 1953–1962.
**Muscovite, biotite.

Table 7

ANGLE OF FOLIATION COMPARED TO ELASTICITY

Foliation	*Angle	Elasticity x 10^6 psi
Well foliated	35^o	0.76–1.64
Well foliated	45^o	0.65–1.30
Foliated	60^o	2.75–5.6
Nonfoliated	90^o	4.48–7.9

*Angle from vertical axis of core

Table 8

MICA COMPARED WITH ELASTICITY AND STRENGTH
MORROW POINT DAM

Percent mica	Elasticity x 10^6 psi	Strength x 10^3 psi
58–68	0.65–0.76	3.5– 4.5
30–40	1.3 –5.8	3 –12
10–16	2.2 –5.6	10 –28
None	7.9	23

Table 9
ABSORPTION COMPARED TO ELASTICITY

Group	Absorption percent	Elasticity x 10^6 psi
I	0.900	2.40
II	0.115	2.18
III	0.332	2.75
III	0.066	3.06
III	0.060	4.52
III	0.066	5.88

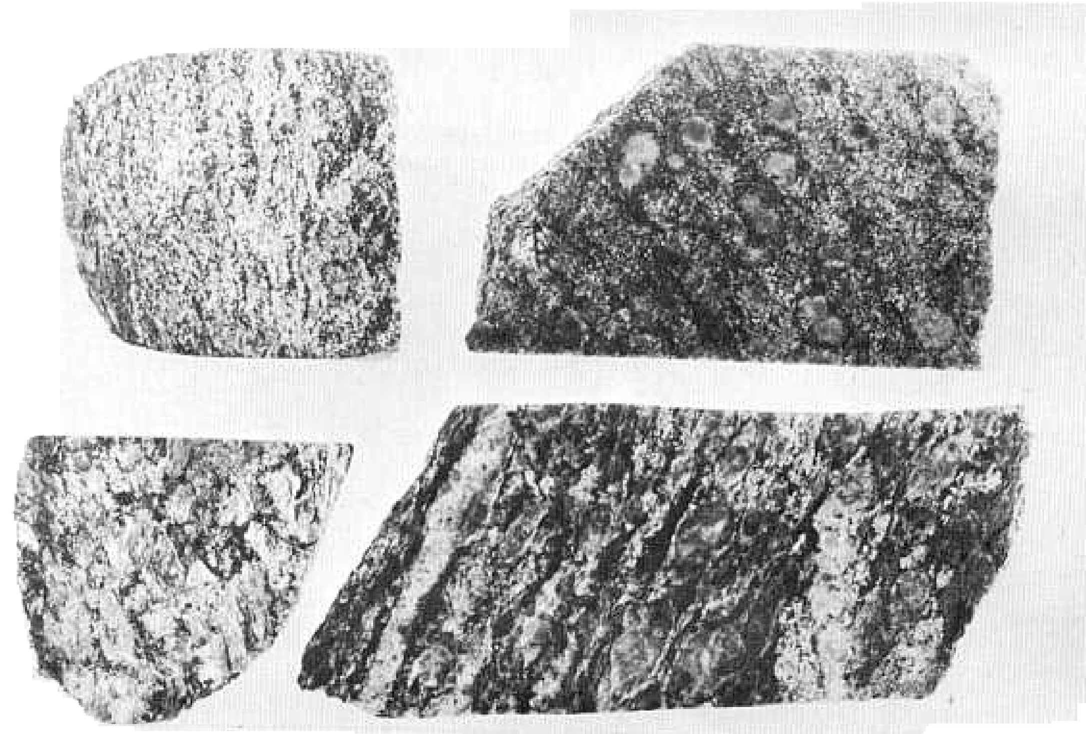


Figure 1. Photograph of quartz, mica-augen schist and mica quartz schist (viewing from top to bottom). Photo PX-D-36286

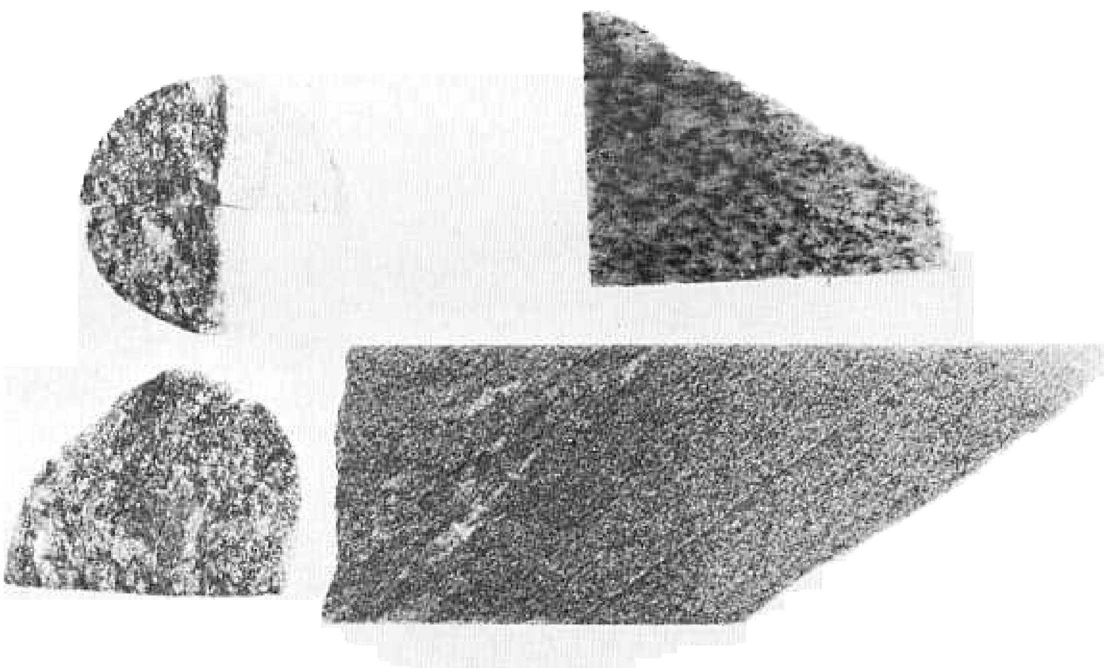


Figure 2. Photograph of horneblende schist and quartz-mica schist (viewing from top to bottom). Photo PX-D-36285

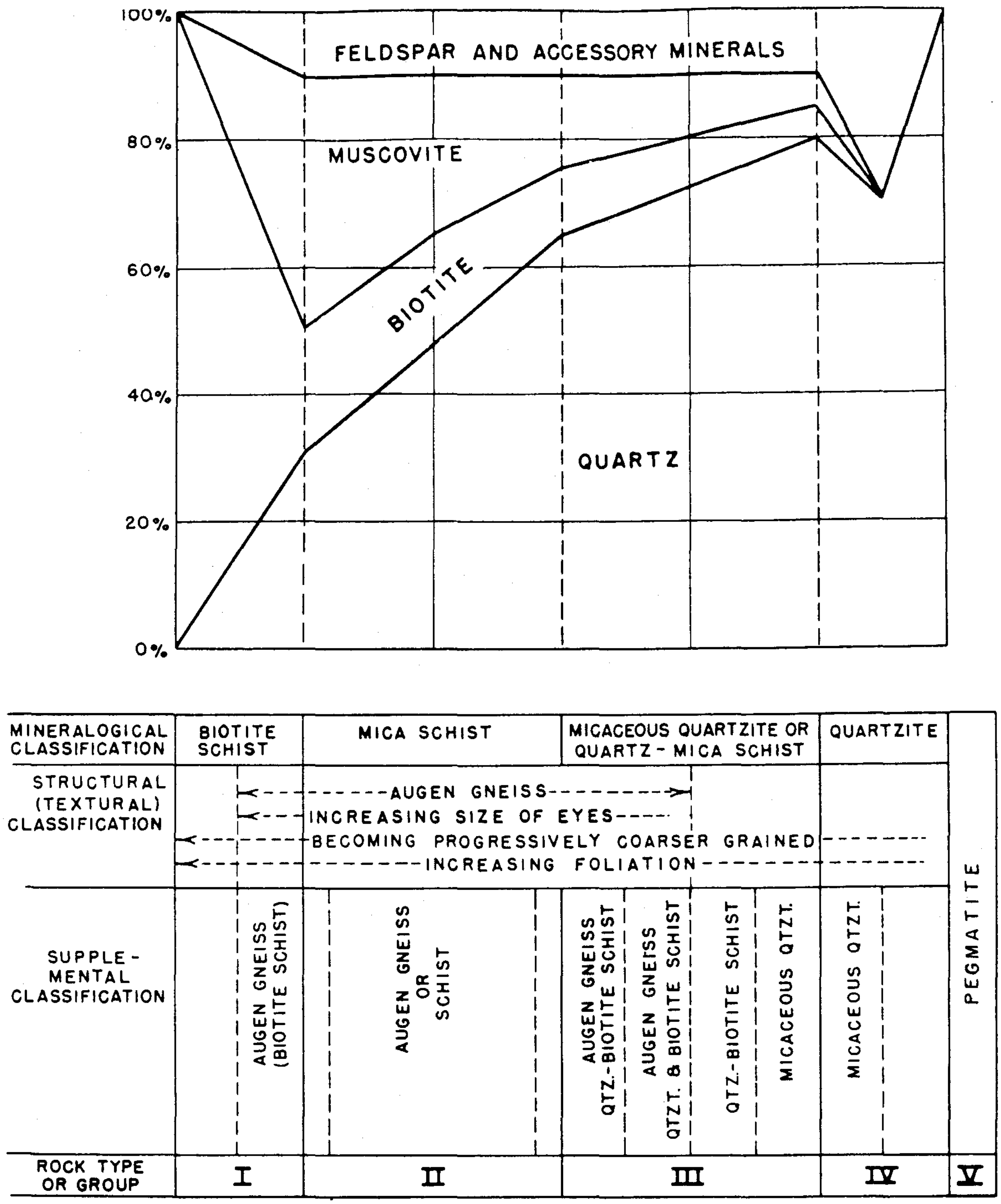


Figure 3. Rock classification relationship—Morrow Point Dam and Powerplant Investigations Bureau of Reclamation, October 1965

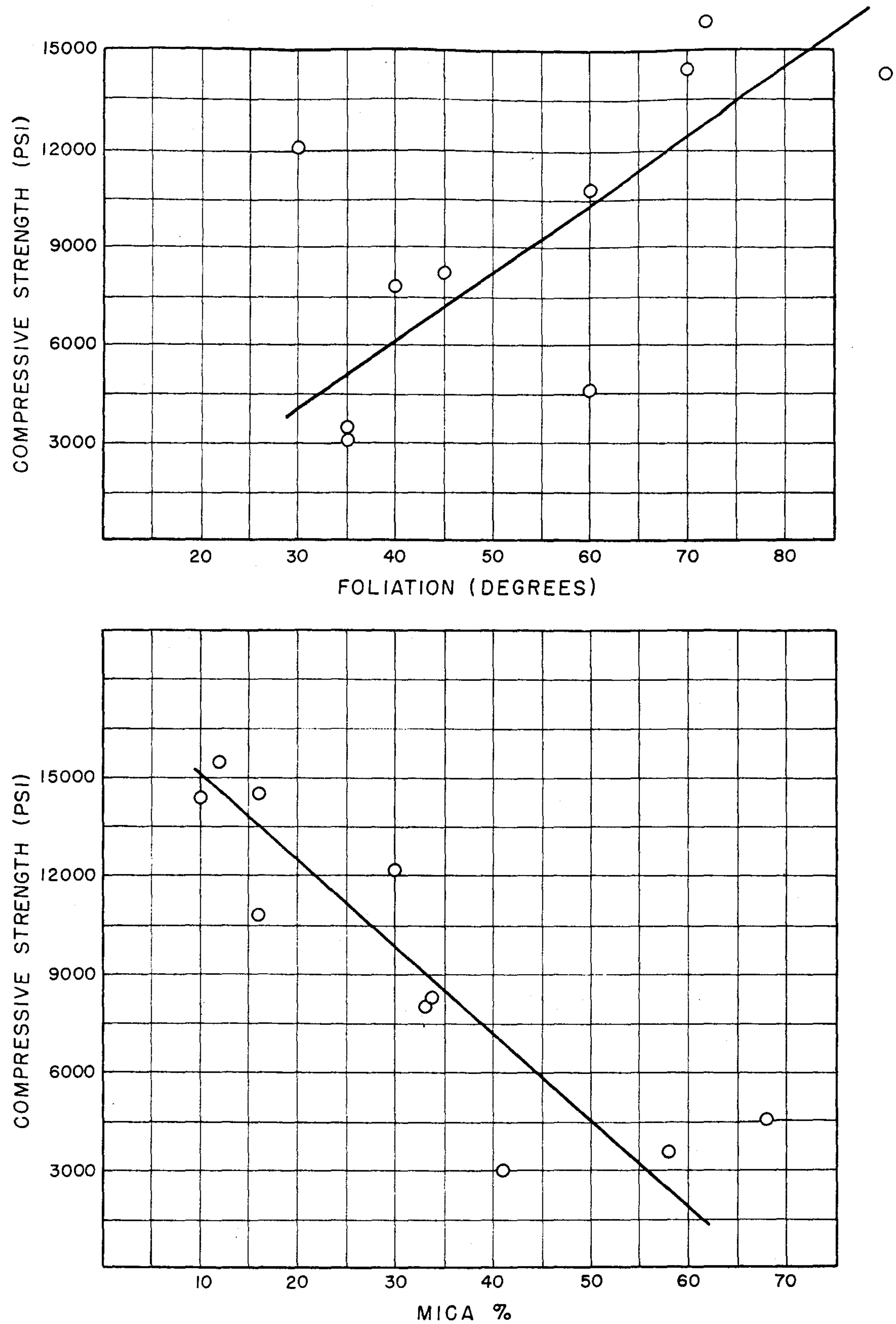


Figure 4. Comparison of percent mica and angle of foliation with strength.

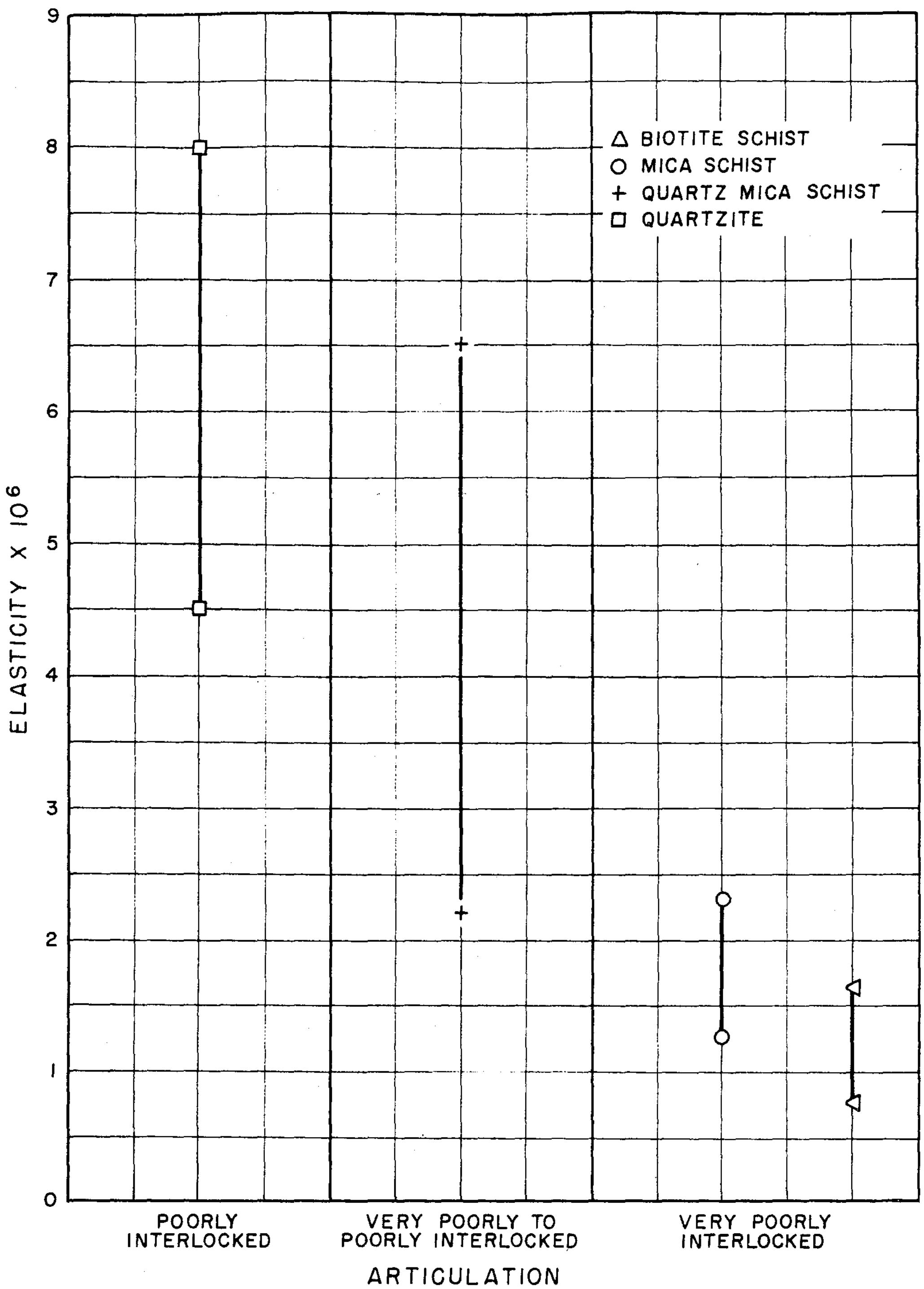


Figure 5. Rock texture versus elasticity.

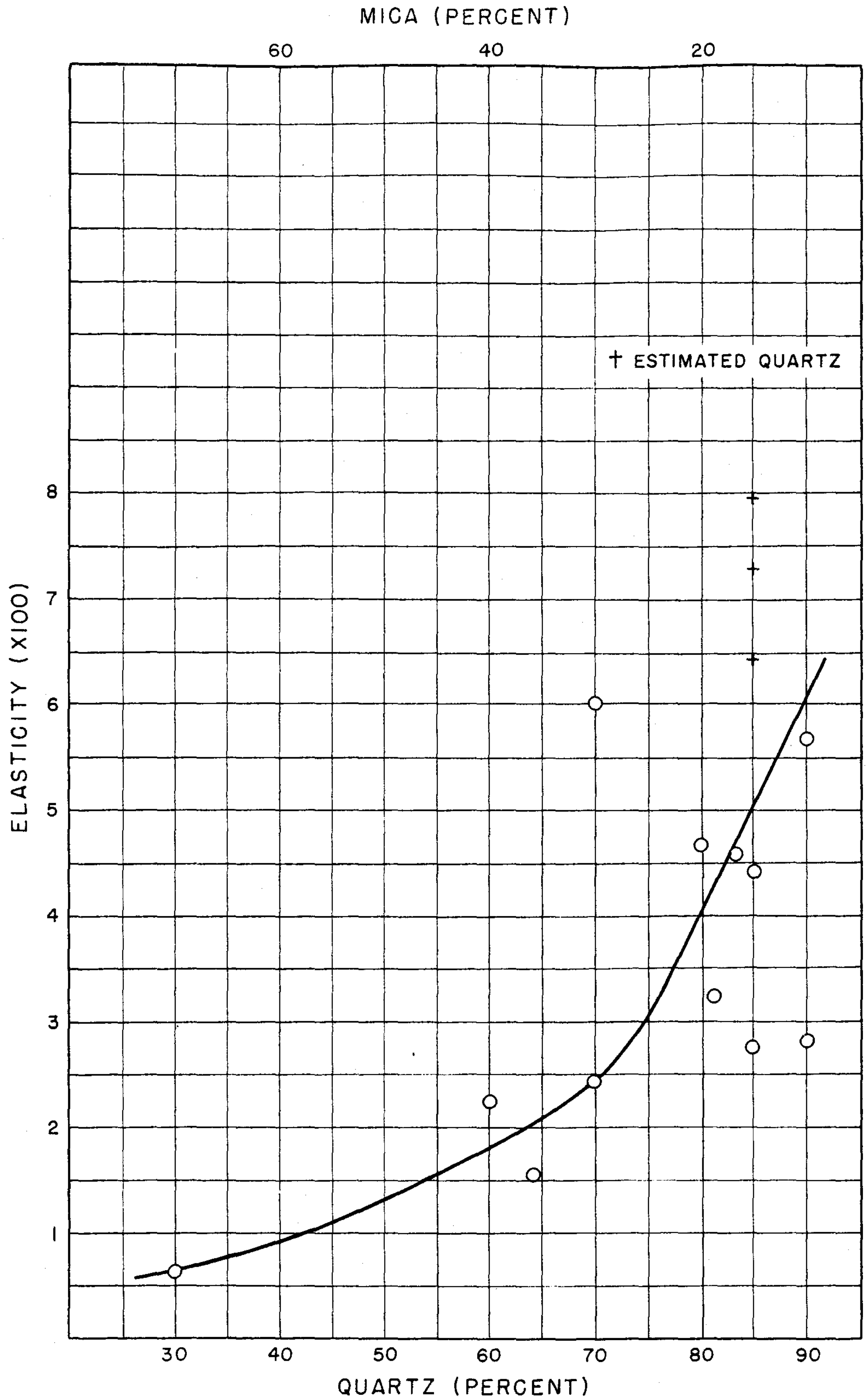


Figure 6. Comparison of percent quartz with elasticity.

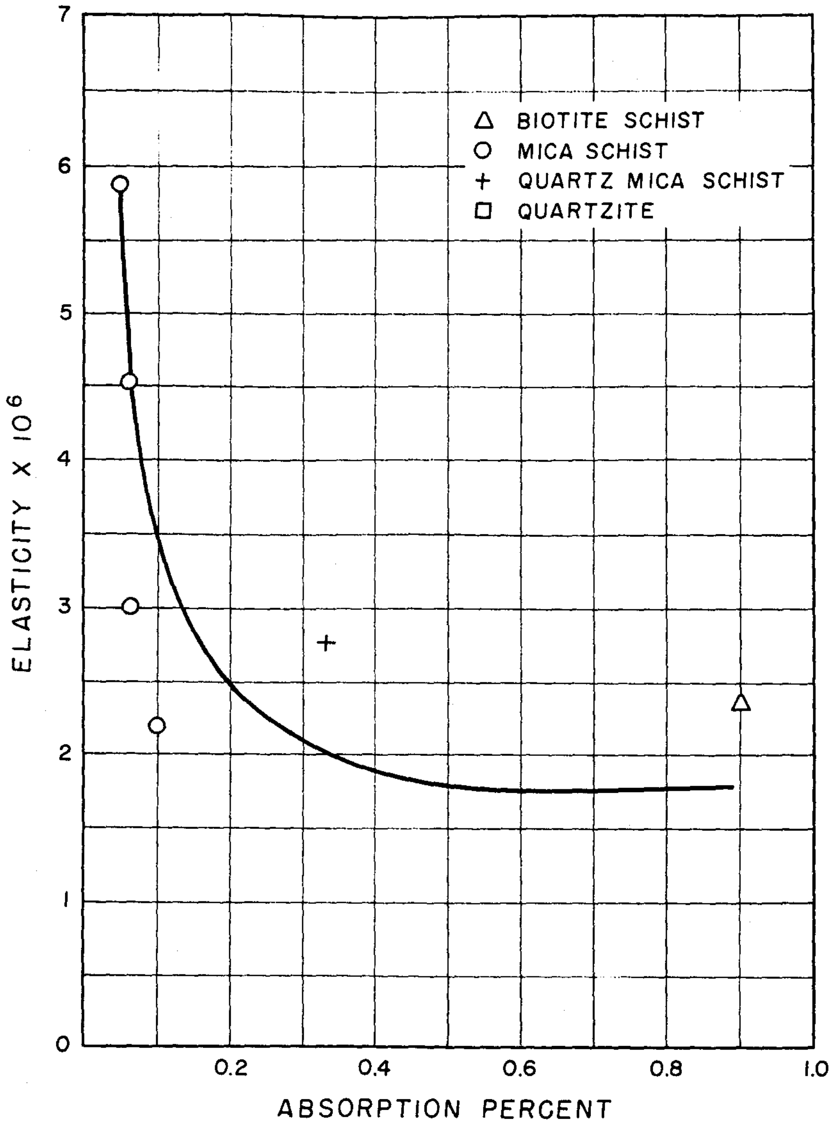


Figure 7. Absorption versus elasticity.

APPENDIX

LITHOLOGIC LOG OF DRILL HOLE 12
MORROW POINT DAMSITE

Rock group	Interval (feet)	Dip °	Description	Condition
	0–25			
II	25–52	79	*Mica Quartz Schist*—medium grained—Micaceous, well foliated, very poorly interlocked 53.–55 feet, at 41–42 *pegmatite,* at 42–52 highly micaceous	Moderately fractured*
III	56–63	–	*Quartz Mica Schist*—medium grained poorly interlocked, quartzose	
II	63–91	72	*Mica Quartz Schist*—medium grained, very poorly interlocked, highly micaceous, well foliated, small amount of *biotite schist, mica augen schist,* at 88–90 feet *pegmatite*	Slightly fractured
III	91–100	–	*Quartz Mica Schist*—medium grained, poorly interlocked, quartzose, at 98–100 *mica quartz schist*	
I	100–109	74	*Muscovite Biotite Schist*—medium to coarse grained, highly micaceous, well foliated, very poorly interlocked	
II	109–170	76	*Mica Quartz Schist*—coarse grained, very poorly interlocked highly micaceous, well foliated at 129 feet *muscovite–biotite schist,* at 150 feet, 167–170 feet *pegmatite,* 164 feet *mica augen schist*	Slight to moderately fractured
III	170–202	55	*Quartz Mica Schist*—medium grained, poorly interlocked, quartzose, at 178–181 feet *muscovite–biotite schist* highly micaceous, 185–190 feet *mica quartz schist,* 195–197 *hornblende schist*	Slightly fractured
	202–209	72	*Alternating Layers of Schist and Pegmatite* —hard, medium to coarse grained	
I	209–236	45	*Muscovite Biotite Schist*—medium grained, highly micaceous, well foliated, very poorly interlocked, some *pegmatite*	
III	236–246	–	*Quartz Mica Schist*—fine grained, poorly interlocked quartzose	Moderately fractured
III	246–266	–	*Mica Augen Schist*—medium grained, very poorly interlocked, quartzose, small amount of *pegmatite,* quartzite	

*Fractured: Slight—Spacing more than 10 feet
Moderate—Spacing 3 to 10 feet
Highly—Spacing less than 12 inches

Group	Total (feet)	Percent total	E x 10^6 psi (average)
I	10	6	0.86
II	4	3	1.20
III	42	27	4.14
II and III	59	38	1.79
III and IV	18	11	1.94
IV	20	13	8.84
V	3	2	2.68

Plate 1. Photomicrograph of Muscovite-biotite Schist (P-7075) composed of coarse-grained euhedral mica (showing cleavage planes) and anhedral quartz. Minor sillimanite, clay and iron oxide also occur. The grains are poorly interlocked and the rock is well foliated.
Polarized light Magnification 10X Photo PX-D-36283

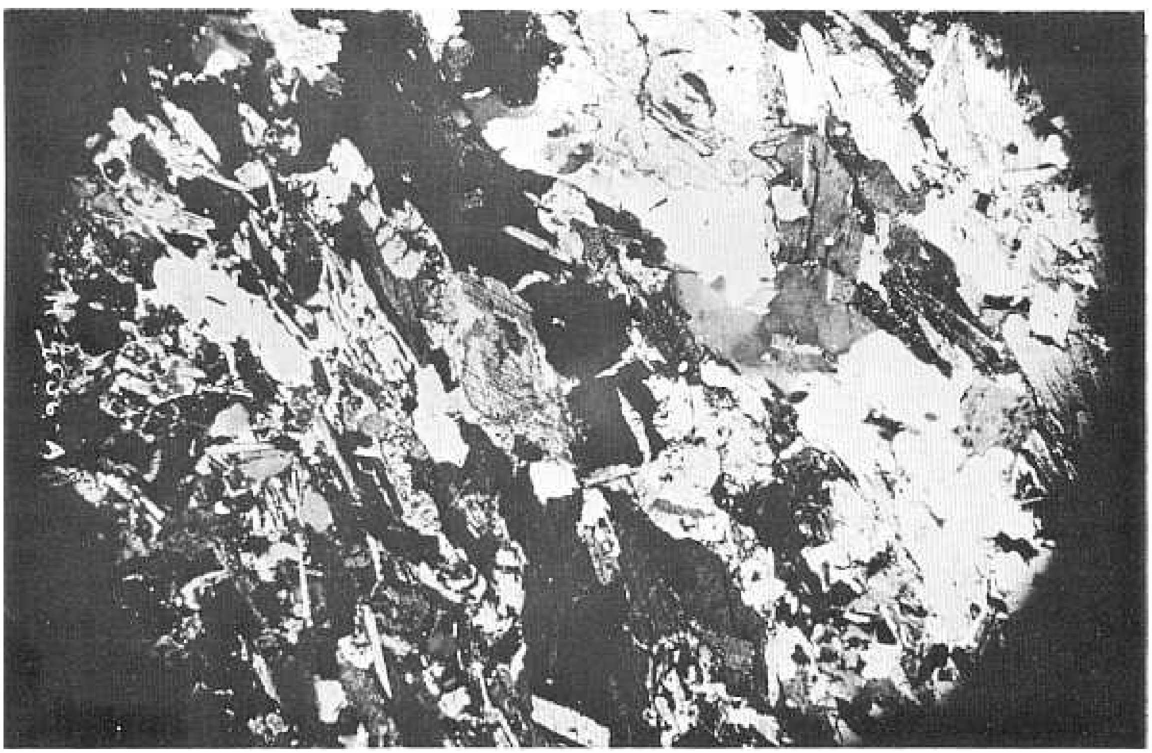


Plate 2. Photomicrograph of Mica-quartz Schist (P-7074) composed of medium-grained euhedral mica and anhedral quartz. The grains have smooth grain boundaries and are poorly interlocked. The mica is frequently alined.
Polarized light Magnification 10X Photo PX-D-36284

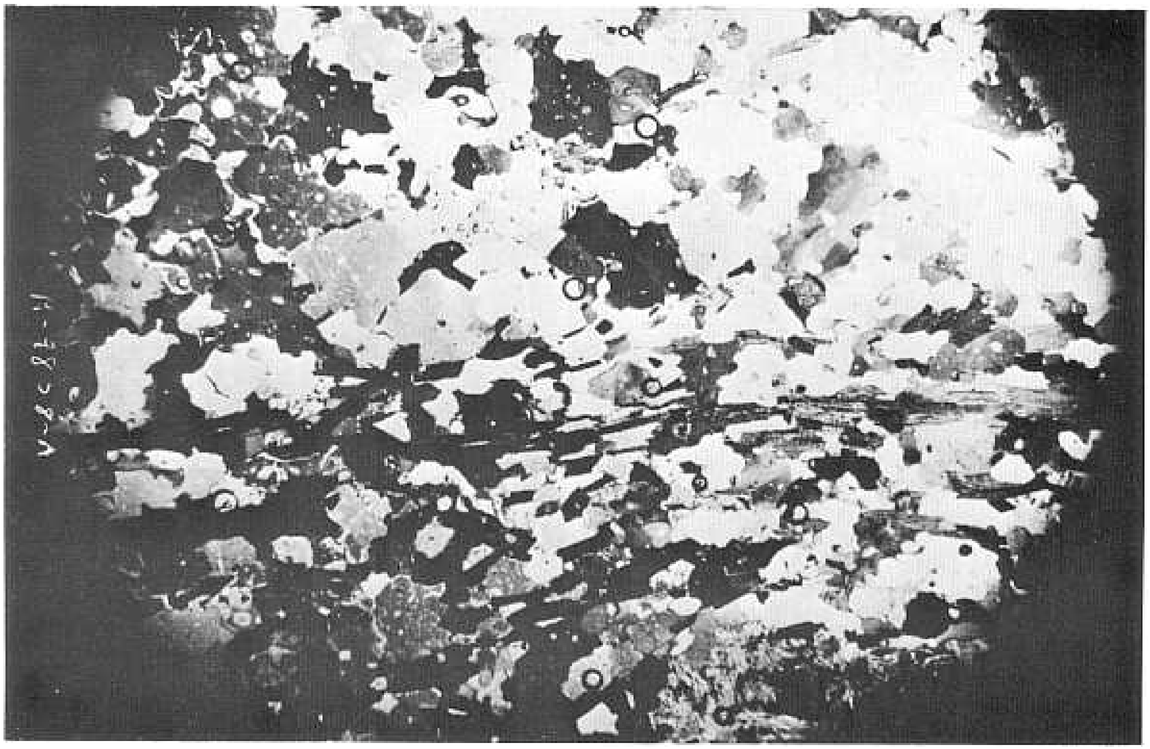


Plate 3. Photomicrograph of Quartz-mica Schist (P-7079) composed of medium-grained anhedral quartz and euhedral mica. The grains exhibit a sutured texture. The mica is alined parallel to itself.
Polarized light Magnification 10X Photo PX-D-36281

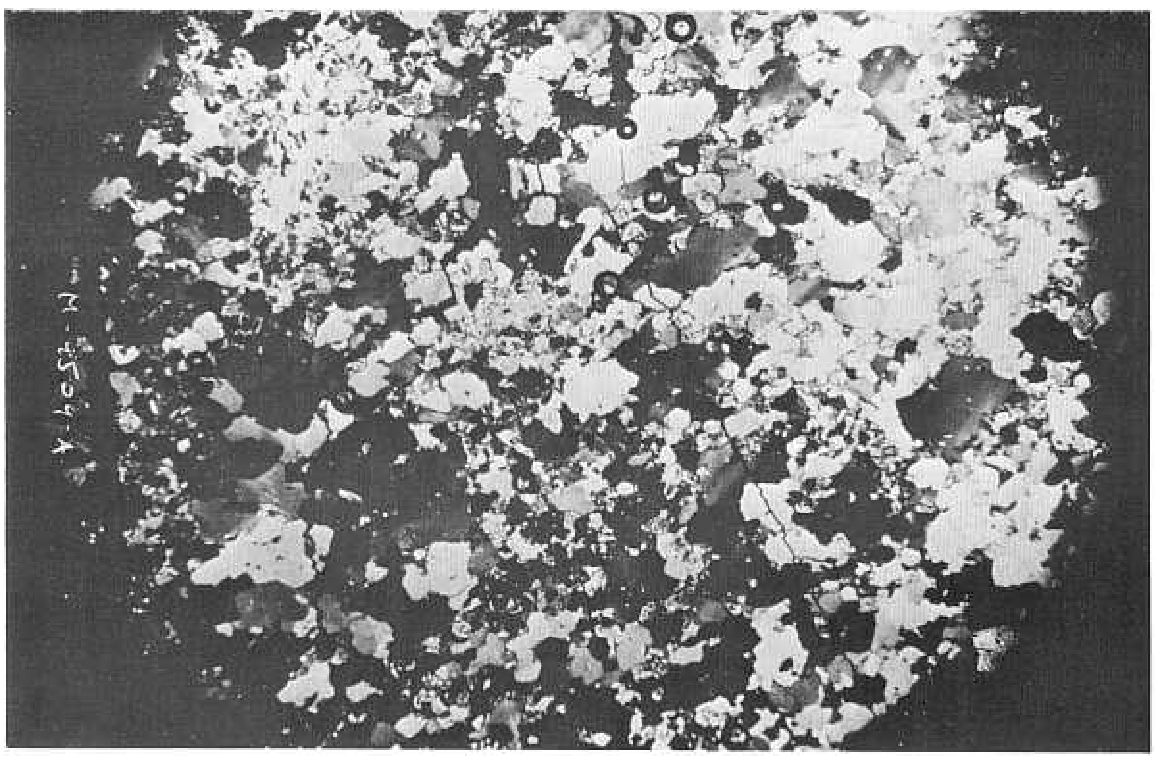


Plate 4. Photomicrograph of Horneblende Schist (P-7077) composed of anhedral quartz and subhedral horneblende. The rock is medium-grained with a sutured texture.
Polarized light Magnification 10X Photo PX-D-36282

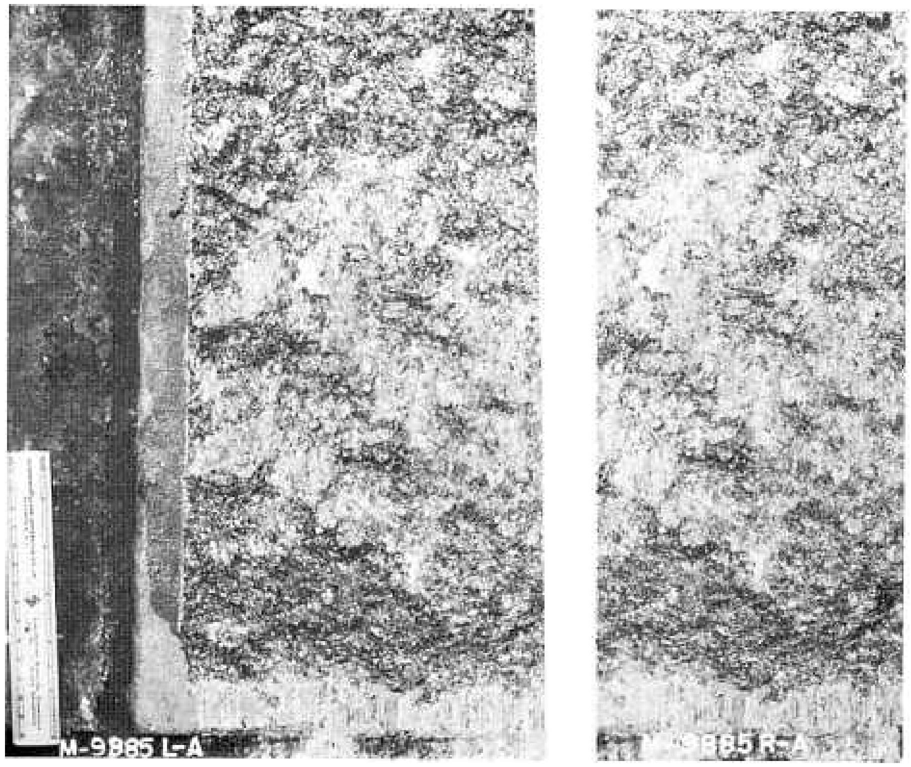


Plate 5. Stereo-pair of sheared surface of rock (Block No. 1) Leftside. Photo PX-D-45609NA

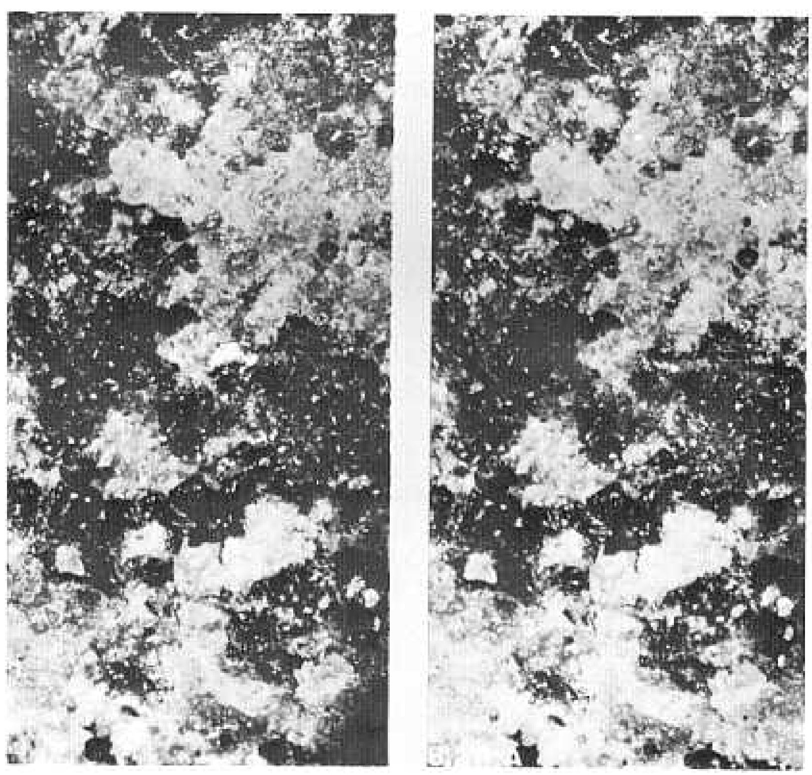
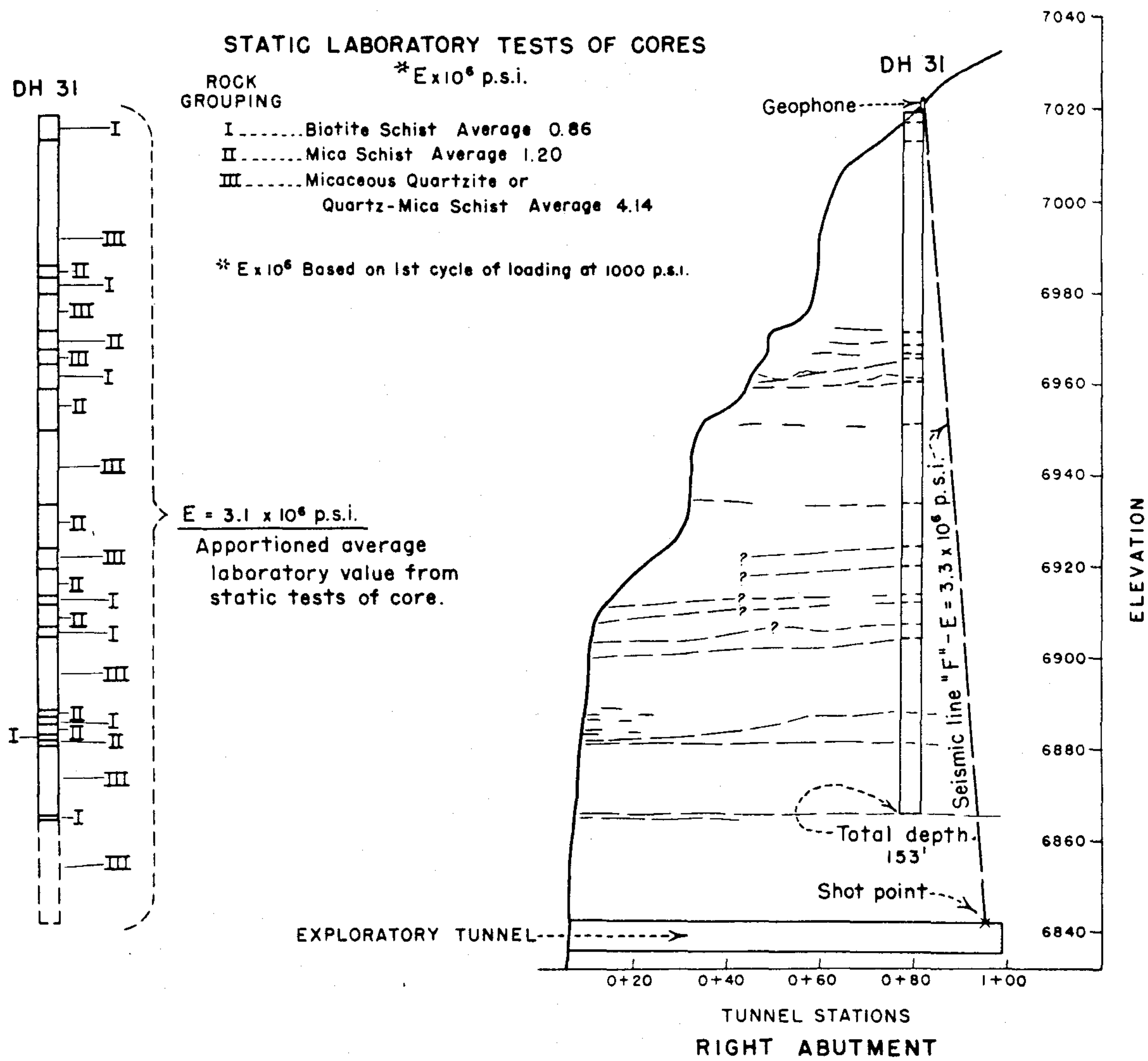


Plate 6. Stereo-pair of rock surface showing rough places (Asperites) (Magnification 16X). Photo PX-D-45610NA



MORROW POINT DAM

Seismic measurements of rock elasticity.

Morrow Point Dam and Powerplant Investigations
Bureau of Reclamation, October 1965

CONVERSION FACTORS--BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg; that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
	0.3048 (exactly)*	Meters
	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	929.03*	Square centimeters
	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	0.40469*	Hectares
	4,046.9*	Square meters
	0.0040469*	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
	0.473166	Liters
Quarts (U.S.)	946.358*	Cubic centimeters
	0.946331*	Liters
Gallons (U.S.)	3,785.43*	Cubic centimeters
	3.78543	Cubic decimeters
	3.78533	Liters
	0.00378543*	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	764.55*	Liters
Acre-feet	1,233.5*	Cubic meters
	1,233,500*	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
	MASS	
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
	FORCE/AREA	
Pounds per square inch	0.070307	Kilograms per square centimeter
	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
	47.8803	Newtons per square meter
	MASS/VOLUME (DENSITY)	
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
	MASS/CAPACITY	
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
	BENDING MOMENT OR TORQUE	
Inch-pounds	0.011521	Meter-kilograms
	1.12985×10^{6}	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
	1.35582×10^{7}	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
	VELOCITY	
Feet per second	30.48 (exactly)	Centimeters per second
	0.3048 (exactly)*	Meters per second
Feet per year	0.965873×10^{-6}*	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
	0.44704 (exactly)	Meters per second
	ACCELERATION*	
Feet per second^2	0.3048*	Meters per second^2
	FLOW	
Cubic feet per second (second-feet)	0.028317*	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
	FORCE*	
Pounds	0.453592*	Kilograms
	4.4482*	Newtons
	4.4482×10^{-5}*	Dynes

Multiply	By	To obtain
	WORK AND ENERGY*	
British thermal units (Btu)	0.252*	Kilogram calories
	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	1.35582*	Joules
	POWER	
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
	HEAT TRANSFER	
Btu in./hr ft^2 deg F (k, thermal conductivity)	1.442	Milliwatts/cm deg C
	0.1240	Kg cal/hr m deg C
Btu ft/hr ft^2 deg F	1.4880*	Kg cal m/hr m^2 deg C
Btu/hr ft^2 deg F (C, thermal conductance)	0.568	Milliwatts/cm^2 deg C
	4.882	Kg cal/hr m^2 deg C
Deg F hr ft^2/Btu (R, thermal resistance)	1.761	Deg C cm^2/milliwatt
Btu/lb deg F (c, heat capacity)	4.1868	J/g deg C
Btu/lb deg F	1.000*	Cal/gram deg C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
	0.09290*	M^2/hr
	WATER VAPOR TRANSMISSION	
Grains/hr ft^2 (water vapor transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	304.8*	Liters per square meter per day
Pound-seconds per square foot (viscosity)	4.8824*	Kilogram second per square meter
Square feet per second (viscosity)	0.092903*	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	35.3147*	Millicuries per cubic meter
Milliamps per square foot	10.7639*	Milliamps per square meter
Gallons per square yard	4.527219*	Liters per square meter
Pounds per inch	0.17858*	Kilograms per centimeter

ABSTRACT

During the foundation investigation of schists and gneisses at Morrow Point damsite, the rock (Nx cores) was petrographically described and classified for structural tests. Petrographic and physical tests of the core were grouped to give an overall picture of the foundation. Methods are described for determining the petrographic characteristics such as articulation, mineral composition, and microstructure of the rock. Articulation and texture of the grains were determined on the basis of microscope examination for evaluation of bond strength. Composition of the rock was determined by modal analysis (by a method of intercept distances) and the rocks were grouped according to minerals present. Oriented microstructures in foliated rocks were determined by the photometer method for analysis of structure. The relationship between elasticity and the texture, composition, and structure was compared. The relationship between absorption and seismic wave velocity was examined. Physical properties by means of laboratory and seismic methods were measured for individual rock types.

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REC-OCE-70-39
Rubenstein, S R
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Bur Reclam Lab Rep REC-OCE-70-39, Appl Sci Br, Oct 1970. Bureau of Reclamation, Denver, 23 p, 8 fig, 12 tab, 6 plate, 8 ref, append

DESCRIPTORS–/ *petrographic investigations/ *rock foundations/ rock mechanics/ gneisses/ mineralogy/ petrofabrics/ compressive strength/ elasticity/ geology/ microstructures/ mica/ *physical properties/ *rock properties/ absorption/ schists/ specific gravity/ static tests
IDENTIFIERS–/ Morrow Point Dam, Colo/ photomicrographs/ thin sections

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