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A Standard Rock Suite for Rapid Excavation Research

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A STANDARD ROCK SUITE FOR RAPID EXCAVATION RESEARCH

by

Warren W. Krech,[1] Frank A. Henderson,[2] and Kenneth E. Hjelmstad[3]

ABSTRACT

Rock property data is needed over a wide range of parameters for the optimum execution of rapid excavation research. Eight rock types were chosen by the Bureau of Mines for a standard rock suite for such research. Large rock blocks were quarried and the standard physical and mechanical properties measured and documented. The eight rock types that comprise the rock suite are Barre Granite, Berea Sandstone, Dresser basalt, Holston Limestone, Salem Limestone, Sioux Quartzite, St. Cloud Gray Granodiorite, and Westerly Granite. Geologic, petrographic, physical-property, and mechanical-property test data are reported for each rock type. The information is the first step in the building of a comprehensive property listing for the eight rock types. A limited number of rock cubes are available from the Bureau of Mines Twin Cities Mining Research Center for use by researchers to broaden the information available on the suite.

INTRODUCTION

Early in the Rock Mechanics and Rapid Excavation research program sponsored by the Advanced Research Projects Agency (ARPA), it became obvious that a single supply of rock was required to fulfill the needs of the various groups conducting research within the program. It was felt that a single supply would prevent each researcher from wasting time and money in the quest of suitable rocks. Furthermore, a single supply of rock could be stocked and maintained with proper precaution given to sample selection, orientation, and documentation; a single operation could be conducted with greater overall economy than could a myriad of small, scattered rock supply operations.

A suite of eight rock types was, therefore, selected by the Bureau of Mines for use by various groups in rapid excavation research. The suite was selected based on their availability of rock in large and fairly homogeneous lots and on the likely pertinence of their properties to the ARPA program requirements. Table 1 gives a listing of the rock types and their source

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[1]Mining engineer.
[2]Geophysicist (now with Soils and Materials Engineering, Inc., Detroit, Mich.).
[3]Geophysicist.

location. Blocks of approximately 40 cu ft were obtained for each rock type, with the blocks oriented with respect to in situ orientation for five of the eight types. Each large block was cut into approximately forty 1-ft cubes, with all orientation marks preserved on each cube.

TABLE 1. - Suite of rocks for ARPA contractors

Rock type	Geologic name	Location
Granodiorite................	Barre Granite..............	Barre, Vt.
Feldspathic sandstone.......	Berea Sandstone............	Amherst, Ohio.
Hornblende biotite basalt...	Dresser basalt.............	Dresser, Wis.
Bioclastic limestone........	Holston Limestone (Tennessee marble).	Friendsville, Tenn.
Brecciated limestone........	Salem (Indiana) Limestone..	Bedford, Inc.
Quartzite...................	Sioux Quartzite............	Jasper, Minn.
Granodiorite................	St. Cloud Gray Granodiorite (Charcoal granite).	Cold Spring, Minn.
Do....................	Westerly Granite...........	Westerly, R.I.

Property data for the selected rocks have many applications in rapid excavation research. Unfortunately, data for a given rock type are not always available in literature over a wide range of parameters significant to the particular research application. Since the expense of conducting a wide variety of tests on a rock type is usually too great in time and monies for each research group to justify, it was decided that certain physical and mechanical properties should be provided along with the rock blocks supplied to the research groups. Establishing a set of property data for each rock type could then be accomplished at very little extra expense and would save the various researchers from expending redundant effort to develop these data. The researcher could then concentrate on obtaining specialized information related to his particular research problem, much of which could then be added to a central file for that rock type.

Accordingly, standard physical property tests were performed on each rock type. The results of those tests, along with a background geologic sketch, are presented for each of the eight rock types. Three cubes from along a diagonal line through the large block were selected as specimen sources for laboratory testing in order to establish the degree of homogeneity of the large blocks as well as to provide a representative sampling.

ACKNOWLEDGMENTS

The information presented was prepared as part of an in-house research project supported by the Advanced Research Projects Agency under its Rock Mechanics and Rapid Excavation program. Special acknowledgment is made of the contributions of Robert C. Steckley, Geologist, Twin Cities Mining Research Center, for providing thin-section photographs and Norman G. Adamson, Geologist, Twin Cities Metallurgy Research Center, for providing the modal analyses of the eight rock types.

DESCRIPTION OF PROPERTY TEST METHODS

A set of standard procedures was used to prepare the samples and to determine the physical properties for each rock type. From each of the three 1-cu-ft blocks a 3-inch sphere, ten 1-inch-diameter by 4-inch-long cores, and ten 1-inch-diameter by 1-inch-long cores were cut. After the acoustic measurements were made on the 4-inch-long cores, they were cut in half and 10 samples each were prepared for compression and tension tests. The Shore hardness measurements were made on the tension test specimens. The ten 1-inch-diameter by 1-inch-long cores were cut for porosity and permeability measurements.

Acoustic Anisotropy

The 3-inch spheres were prepared (13)[4] for the acoustic anisotropy measurements with the Z-axis in the up direction and the X-axis horizontal in the direction of the orientation mark on the block. The prepared specimens were dried for a minimum of 5 days in a vacuum oven at 150° F. Longitudinal pulse velocities were measured in 73 directions at a room environment of approximately 75° F and 40 pct relative humidity. The velocity measurements were plotted on a lower hemisphere equal-area projection grid and contoured with isovelocity lines (5). The high (V_{max}) and low (V_{min}) velocities were determined from this plot, and percent anisotropy (A) was computed using the formula

$$A = \frac{V_{max} - V_{min}}{1/2\ (V_{max} + V_{min})} \times 100.$$

The elastic symmetry system of the rock was determined from the pattern of the contoured stereoplot.

Dynamic Properties

The 1-inch cores for dynamic testing were prepared with the long axis perpendicular to the top face of the block, which corresponds to the Z direction on the stereonet plots of velocity. The specimens were dried for a minimum of 5 days in a vacuum oven at 150° F prior to pulse velocity measurement. Longitudinal and shear pulse velocities measurements were obtained on an ultrasonic pulse bench (12). The dynamic elastic constants were calculated from the velocities and the specimen density, using equations derived with the assumption of isotropy.

Physical Properties

Porosity and permeability measurements were made on the 1-inch-long specimens. Prior to measurement, the specimens were ultrasonically cleaned in distilled water through 3 cycles of 5 minutes each, then dried at 212° F for 72 hours prior to testing. Porosity was measured by the pressurized helium

[4] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

and mercury barometer method, and permeability by a commercial permeameter capable of detecting liquid permeabilities to as low as 1 x 10^{-9} cm/sec.[5]

Shore hardness tests were conducted using the Shore scleroscope.[6] Ten readings were taken on each specimen, and the average value determined. The coefficient of variation was calculated using the average value for each specimen.

Static Properties

The specimens for compression and tension tests were prepared by halving the 4-inch-long cores used for the dynamic properties measurements and grinding of the new specimen ends. The specimens were prepared according to specifications set forth by ASTM guidelines for sample preparation (1-2). An MTS Systems Corporation material testing system was used for both the tension and compression tests. Constant specimen deformation rate was applied to the specimen by the programed closed-loop electrohydraulic servocontrolled system. The deformation rate was controlled at a level corresponding to a strain rate of 1 x 10^{-5} cm/cm/sec for the compression tests and 1.6 x 10^{-6} cm/cm/sec for the tension tests (6). Moduli values are tangent values fit to the highest value slope in the central half of the applied load range. (Several of the rock types showed extremely nonlinear load-deformation curves in either or both the tension and compression regions.)

ROCK SUITE DESCRIPTION

Barre Granite

Geologic Occurrence

Barre Granite occurs in an elongate body about 4 miles in length, trending north-northeast, in the east-central region of Vermont just outside the town of Barre, Vt. The granite resists erosion and occurs in two prominent knobs or domes which intrude a country rock of schist, quartzite, and metalimestone (Devonian period), which are part of a tremendous thickness of Paleozoic metasediments underlying east-central Vermont (4).

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[5] Permeability, K, is determined by the Darcy relationship

$$K = \frac{q}{Ai},$$

where K = permeability in cm/sec,

q = flow rate in cm^3/sec,

A = area in cm^2,

and i = pressure gradient in cm/cm.

The relationship is for 24° C distilled water as the flowing fluid. Correction for other temperatures or fluids can be made by a ratio of the viscosity of the flowing fluid to that of water at 24° C. The pressure gradient is the change in pressure (expressed in water column height) per unit length of flow path.

[6] Reference to specific brand names is made for identification only and does not imply endorsement by the Bureau of Mines.

The age of the Barre Granite has been estimated as 330±25 million years (Carboniferous period) as determined by the rubidium/strontium method, using the biotite in the rock (9). It is thought to have been emplaced as a magma, which made room for itself by a combination of gentle intrusion and magmatic stoping of the overlying schist. The hypothesis is supported by evidence such as the remarkable uniform nature of the granite, little reaction with wall rock or inclusions, concordancy with country rock, and lack of marginal faults or fracture zones along contacts.

The rock is a massive gray, medium- to fine-grained biotite granite of very uniform texture. The rift trends northeast and is approximately vertical; the grain is horizontal; and the hardway is vertical and trends northwest. There are longitudinal joints which are vertical to steeply dipping, and trend northeast. A few vertical dikes of dark lamprophyre, up to several feet thick, are oriented in a northeasterly direction (4).

Properties

The petrographic description, thin-section photographs, and core surface photograph are shown in figure 1. The equal area plot of the acoustic velocity is shown in figure 2. Barre Granite has an orthotropic elastic symmetry with a velocity anisotropy of over 18 pct. The intermediate value elastic axis is vertical in these blocks with the low value elastic axis 60° to the left of the orientation arrow and the high value elastic axis 30° to the right of the orientation arrow. The arrow indicates the in situ north direction and the block face lying 30° to the right of the arrow is the rift direction in the quarry.

Table 2 gives the physical property, static, and dynamic test results.

TABLE 2. - Barre Granite test results

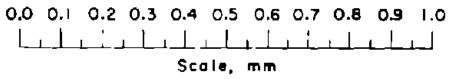
Property[1]	Block No. 1		Block No. 16		Composite	
	Mean	CV[2]	Mean	CV[2]	Mean	CV[2]
Porosity....pct..	0.41	58.3	0.60	33.9	0.51	44.2
Permeability....µm/sec..	([3])	-	([3])	-	([3])	-
Density....g/cm^3..	2.64	0.0	2.64	0.0	2.64	0.9
Shore hardness....	90.3	5.3	87.3	2.6	88.8	4.3
Compressive strength....MN/m^2..	205	9.96	189	9.78	197	10.5
Do....10^3 psi..	29.8	9.96	27.4	9.78	28.6	10.5
Compressive Young's modulus....GN/m^2..	46.4	12.9	44.8	7.10	45.6	10.4
Do....10^6 psi..	6.73	12.9	6.49	7.10	6.61	10.4
Tensile strength....MN/m^2..	6.68	26.6	8.66	6.79	7.67	21.4
Do....10^3 psi..	0.97	26.6	1.26	6.79	1.11	21.4
Tensile Young's modulus....GN/m^2..	16.8	2.43	18.2	14.3	17.5	20.0
Do....10^5 psi..	25.6	2.43	2.64	14.3	25.4	20.0
Pulse velocity....km/sec..	3.81	0.2	3.77	1.4	3.79	1.1
Bar velocity....km/sec..	3.56	0.7	3.45	4.9	3.51	3.8
Torsional velocity....km/sec..	2.50	0.6	2.45	2.5	2.48	4.9
Dynamic Young's modulus[4]....GN/m^2..	33.5	1.6	31.5	9.6	32.5	7.2
Dynamic shear modulus[4]....GN/m^2..	16.6	1.2	15.8	5.0	16.2	4.2
Poisson's ratio[4]....	0.221	3.8	0.245	15.1	0.233	12.4

[1]Specimen prepared with the long axis perpendicular to the top face (along Z-axis).
[2]Coefficient of variation, percent.
[3]Less than 1×10^{-4} µm/sec.
[4]Calculation is based on the assumption of isotropy.

BARRE GRANITE
Thin section photographs

Thin section at crossed nicols

Thin section plane polarized



3/4-inch-diameter core

No. 3-16

Barre Granite

Color: Light gray

Texture: Medium-grained, granitic, subhedral feldspar and mica grains are surrounded by anhedral quartz.

Phases:		
Plagioclase	-	50.0 pct
Quartz	-	22.0 pct
Microcline	-	10.0 pct
Biotite	-	8.0 pct
Muscovite	-	6.0 pct
Opaque accessory	-	4.0 pct

Classification: Granodiorite

FIGURE 1. - Petrographic description of Barre Granite.

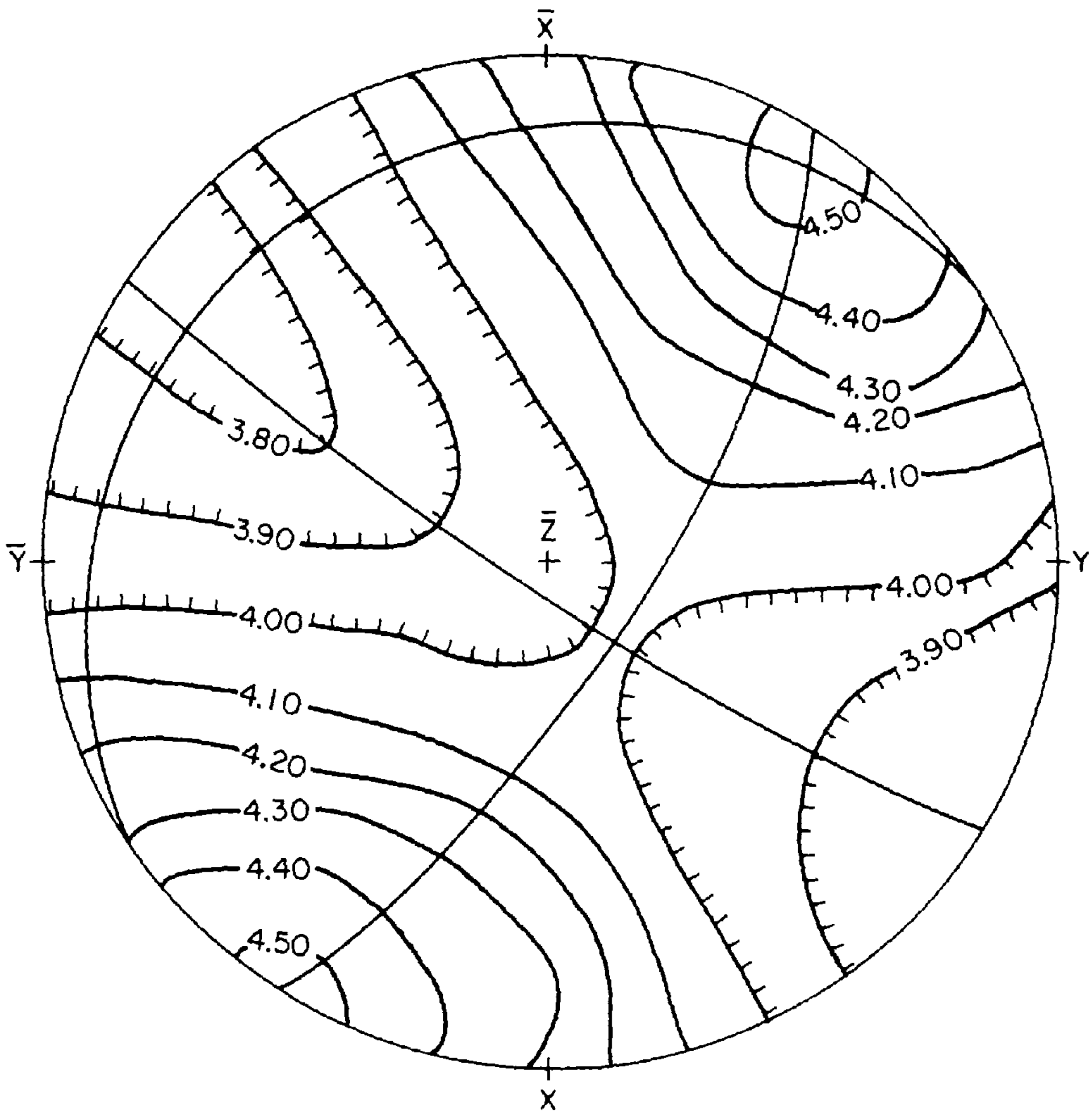


FIGURE 2. - Equal area projection of sonic pulse velocity (km/sec) for Barre Granite.

Berea Sandstone

Geologic Occurrence

Berea Sandstone is a flat-bedded, light gray, medium- to fine-grained protoquartzite with a silica and clay cement. Berea, early Mississippian in age, is underlain by Bedford shale and normally overlain by the Sunbury shale. (In the quarry district this shale has been eroded away and the only overlay are deposits of glacial drift.)

In northern Ohio, Berea Sandstone is made up of two phases: an upper phase consisting of sheet sandstone 20 to 40 ft thick, and a lower phase, a massive sandstone which fills deeply cut channels (up to 250 ft deep) into the Bedford shale, in which the quarries are situated. This thick channel sandstone is remarkably free of contamination; scattered plant fragments and thin seams of coaly material make up less than 1 pct of the bulk of the stone.

Both the Bedford shale and Berea Sandstone were deposited by distributaries of the "Ontario River" entering a sea from the north. After its deposition and consolidation, the Bedford shale was uplifted, and the rejuvenated distributaries cut deeply into the Bedford shale. At the time the Berea Sandstone was deposited, the river became overloaded with sand, filled the entrenched channels, and then spread laterally to form the sheet sandstone of the upper phase (4).

Properties

The petrographic description, thin-section photographs, and core surface photograph are shown in figure 3. The equal area plot of the acoustic velocity is shown in figure 4. Berea Sandstone has an orthotropic elastic symmetry with 9.3 pct velocity anisotropy. The low value elastic axis is nearly vertical with the high value elastic axis 10° to the right of the orientation arrow and dipping at about 30° below the horizontal plane. The orientation arrow is not related to an in situ direction other than being on the in situ upper face. Cross bedding in this sandstone is known to be a common occurrence.

Table 3 gives the physical property, static, and dynamic test results.

TABLE 3. - Berea Sandstone test results

Property[1]	Block No. 5		Block No. 13		Block No. 21		Composite	
	Mean	CV[2]	Mean	CV[2]	Mean	CV[2]	Mean	CV[2]
Porosity....................pct..	19.1	2.0	19.3	3.0	19.0	3.1	19.1	2.7
Permeability.............μm/sec..	0.56	47.1	0.69	36.6	0.58	39.3	0.61	40.5
Density....................g/cm^3..	2.11	0.5	2.11	0.6	2.11	0.5	2.11	0.6
Shore hardness....................	32.9	7.4	32.1	12.6	30.3	9.2	31.8	10.2
Compressive strength.......MN/m^2..	44.5	8.5	46.2	8.4	46.2	7.4	46.2	7.9
Do.................10^3 psi..	6.45	8.5	6.70	8.4	6.70	7.4	6.70	7.9
Compressive Young's modulus GN/m^2..	14.3	13.4	15.7	11.8	13.9	8.6	13.8	12.3
Do.................10^6 psi..	2.08	13.4	2.27	11.8	2.02	8.6	2.00	12.3
Tensile strength..........MN/m^2..	0.984	9.96	1.03	8.9	1.17	18.2	1.07	15.4
Do.................10^3 psi..	0.143	9.96	0.149	8.9	0.171	18.2	0.155	15.4
Tensile Young's modulus....GN/m^2..	1.81	16.6	-	-	1.30	29.2	1.49	28.8
Do.................10^6 psi..	0.262	16.6	-	-	0.188	29.2	0.216	28.8
Pulse velocity...........km/sec..	2.40	1.2	2.50	1.5	2.45	1.6	2.45	2.1
Bar velocity.............km/sec..	1.91	2.8	2.09	2.6	2.03	1.6	2.01	4.5
Torsional velocity........km/sec..	1.40	2.7	1.51	2.2	1.46	1.7	1.46	4.0
Dynamic Young's modulus[3]...GN/m^2..	7.72	6.0	9.28	5.7	8.71	3.5	8.50	9.0
Dynamic shear modulus[3].....GN/m^2..	4.11	5.9	4.88	5.0	4.52	3.9	4.45	8.3
Poisson's ratio[3]................	0.346	2.8	0.317	2.9	0.325	2.6	0.329	4.6

[1]Specimen prepared with the long axis perpendicular to the top face (along Z-axis).
[2]Coefficient of variation, percent.
[3]Calculation is based on the assumption of isotropy.

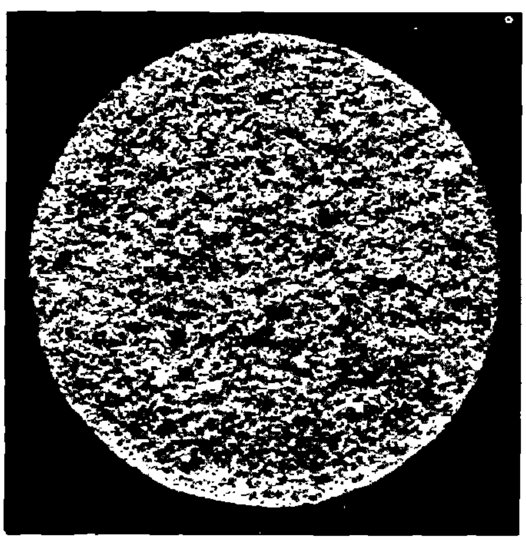
BEREA SANDSTONE
Thin section photographs

Thin section at crossed nicols

Thin section plane polarized

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Scale, mm



3/4-inch-diameter core

No. 3-5

Berea Sandstone

Color: Light tan

Texture: Massive, granular, sand-size grains of quartz

Phases:		
	Quartz	- 77.5 pct
	Feldspar	- 16.0 pct
	Kaolinite	- 5.0 pct
	Muscovite	- 0.5 pct
	Carbonate	- 0.5 pct

The quartz grains are anhedral to subhedral. The feldspars are equant to elongate to anhedral to euhedral. The quartz and feldspar grains are cemented together by chert. Much altered feldspar is found between quartz and feldspar grains.

Classification: Feldspathic sandstone

FIGURE 3. - Petrographic description of Berea Sandstone.

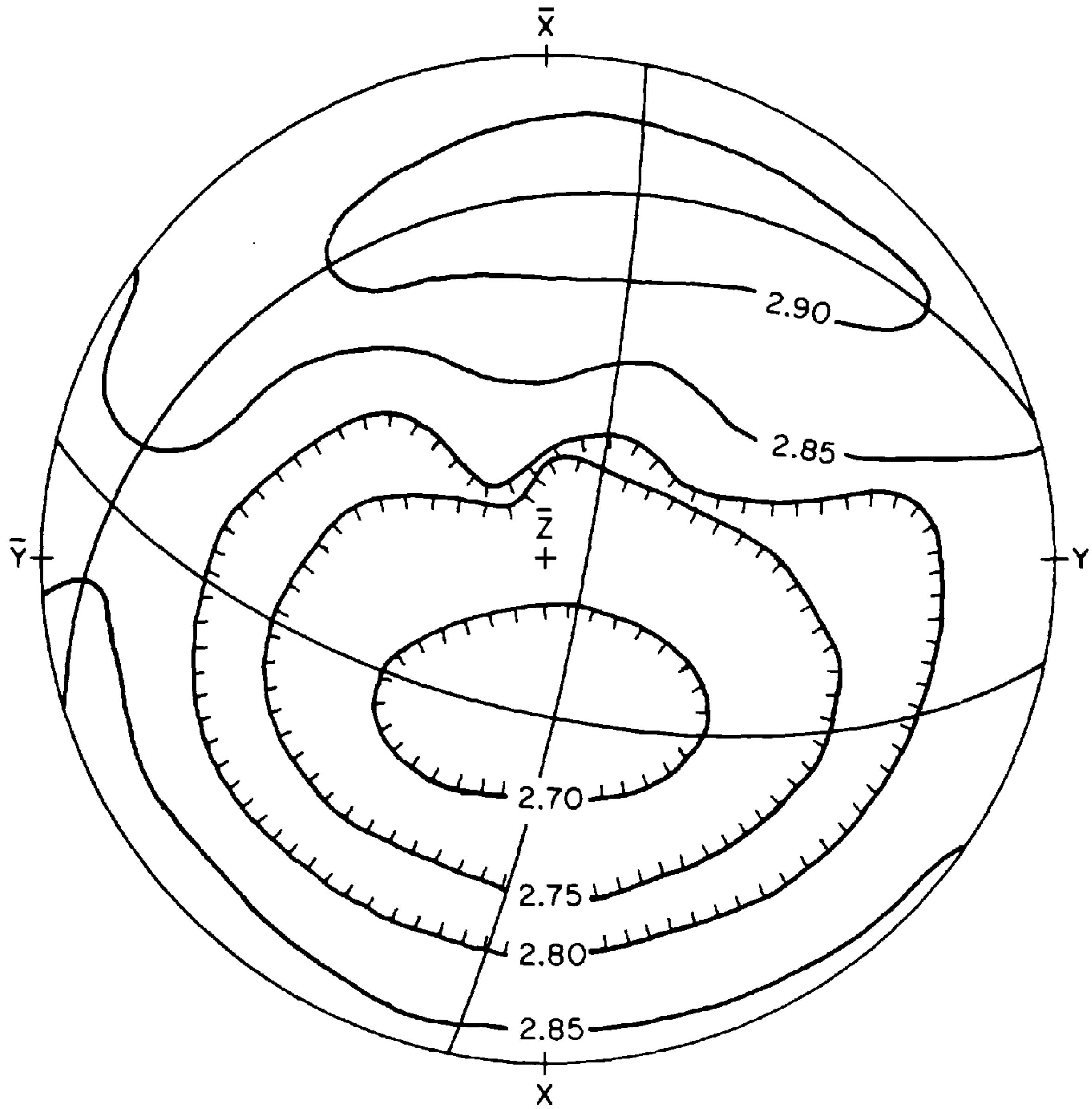


FIGURE 4. - Equal area projection of sonic pulse velocity (km/sec) for Berea Sandstone.

Dresser Basalt

Geologic Occurrence

Dresser basalt from Dresser, Wis., is an altered basalt at the southwestern end of a belt of igneous rocks of the Middle Keweenawan era that trend northeast to Lake Superior. This belt of Precambrian rocks consists mainly of gabbro and basic lava flows with basic and acidic intrusives (8).

The Keweenawan series of the Lake Superior region was formed in late Precambrian time. The first event was the deposition of the lower Keweenawan sediments. The middle Keweenawan is recognized by enormous extrusions of predominantly basic amygdaloidal laval flows with interbedded sandstone and conglomerates. The widespread extent of flows and lack of volcanic ash indicate that the flows came from a fissure or system of fissures rather than from volcanoes. This period of extrusives was followed by the upper Keweenawan period of predominantly continental sedimentary deposition (11).

In the vicinity of Dresser (west-central Wisconsin) the deposit has undergone considerable hydrothermal or deuteric alteration. The rock has been classified as either an altered gabbro or an altered basalt, but the latter term is the one most commonly used.

The deposit is highly jointed and faulted; there is no appearance of any definite joint system; and the strike and dips range through 180°. Two nearly vertical faults cut through the Bryan quarry east-west and north-south. Associated with these two faults are several flat-dipping faults. Because of the irregular fracture pattern, the deposit, as exposed at the quarry, appears in the form of unconsolidated blocks, slabs, and wedges.

Properties

The petrographic description, thin-section photographs, and core surface photograph are shown in figure 5. The equal area plot of the acoustic velocity is shown in figure 6. Dresser basalt has a transversely isotropic elastic symmetry with 2.5 pct velocity anisotropy. The low value elastic axis is 30° to the right of the orientation arrow. This arrow is not related to any in situ direction.

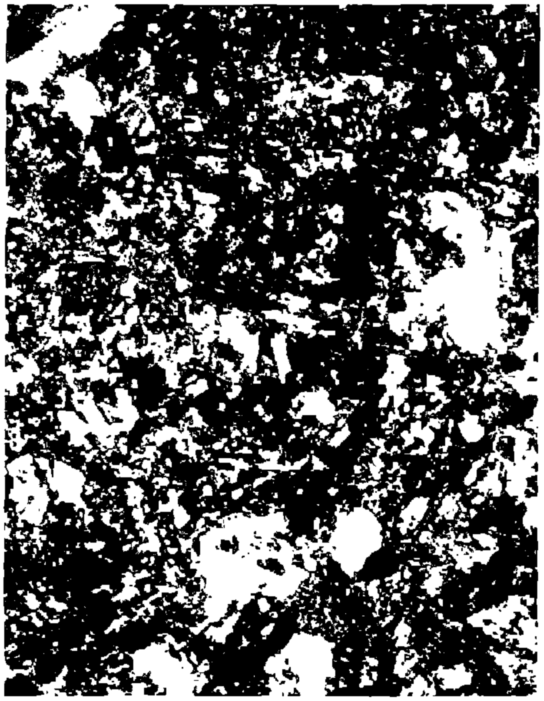
Table 4 gives the physical property, static, and dynamic test results.

TABLE 4. - Dresser basalt test results

Property[1]	Block No. 17		Block No. 28		Block No. 68		Composite	
	Mean	CV[2]	Mean	CV[2]	Mean	CV[2]	Mean	CV[2]
Porosity....................pct..	0.16	9.0	0.15	0.05	0.25	12.7	0.19	57.3
Permeability.............μm/sec..	(3)	-	(3)	-	(3)	-	(3)	-
Density....................g/cm³..	3.02	0.1	3.01	0.7	3.01	0.1	3.01	0.5
Shore hardness....................	95.0	3.1	93.2	2.5	94.2	1.9	94.1	2.6
Compressive strength.......MN/m²..	479	7.91	413	10.7	429	9.16	440	11.0
Do.................10³ psi..	69.5	7.91	59.9	10.7	62.2	9.16	63.9	11.0
Compressive Young's modulus GN/m²..	88.5	2.43	82.1	2.18	87.5	2.42	86.1	4.1
Do.................10⁶ psi..	12.8	2.43	11.9	2.18	12.7	2.42	12.5	4.1
Tensile strength..........MN/m²..	22.9	24	24.0	38.0	17.6	57.0	22.1	39.7
Do.................10³ psi..	3.33	24	3.48	38.0	2.56	57.0	3.20	39.7
Tensile Youngs' modulus....GN/m²..	133	9	121	21	105	23	119	20.2
Do.................10⁶ psi..	19.2	9	17.6	21	15.3	23	17.3	20.2
Pulse velocity...........km/sec..	6.77	0.3	6.67	0.3	6.72	0.3	6.72	0.7
Bar velocity.............km/sec..	6.12	0.2	5.99	0.4	6.04	0.5	6.05	1.0
Torsional velocity........km/sec..	3.86	0.2	3.76	0.4	3.80	0.6	3.80	1.2
Dynamic Young's modulus[4]...GN/m²..	113	0.5	108	1.5	109	1.1	110	2.5
Dynamic shear modulus[4].....GN/m²..	44.9	0.4	42.5	1.5	43.4	1.3	43.6	2.6
Poisson's ratio[4].................	0.261	1.4	0.266	1.1	0.266	1.5	0.264	1.6

[1]Specimen prepared with the long axis perpendicular to the top face (along Z-axis).
[2]Coefficient of variation, percent.
[3]Less than 1×10^{-4} μm/sec.
[4]Calculation is based on the assumption of isotropy.

DRESSER BASALT
Thin section photographs

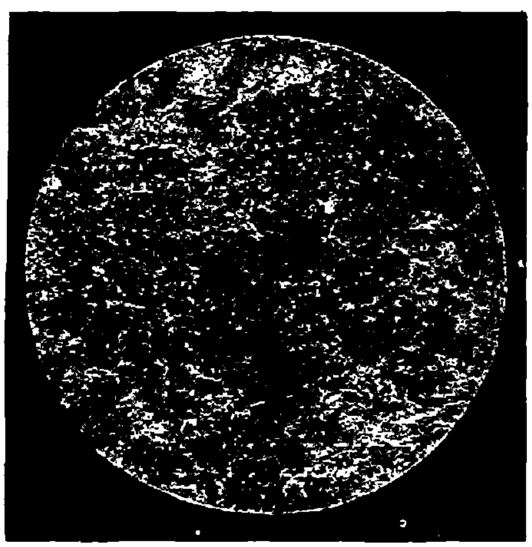


Thin section at crossed nicols

Thin section plane polarized

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Scale, mm



3/4-inch-diameter core

No. 3-68

Dresser basalt

Color: Dark grayish green

Texture: Ophitic, massive, fine grained

Phases:		
	Plagioclase	- 41.4 pct
	Pyroxene	- 40.4 pct
	Chlorite	- 6.0 pct
	Magnetite	- 5.3 pct
	Amphibole	- 1.9 pct
	Sericite	- 4.7 pct
	Hematite	- 0.3 pct

Much of the original pyroxene is altered to amphibole chlorite. Plagioclase shows considerable alteration to sericite.

Classification: Hornblende biotite basalt

FIGURE 5. - Petrographic description of Dresser basalt.

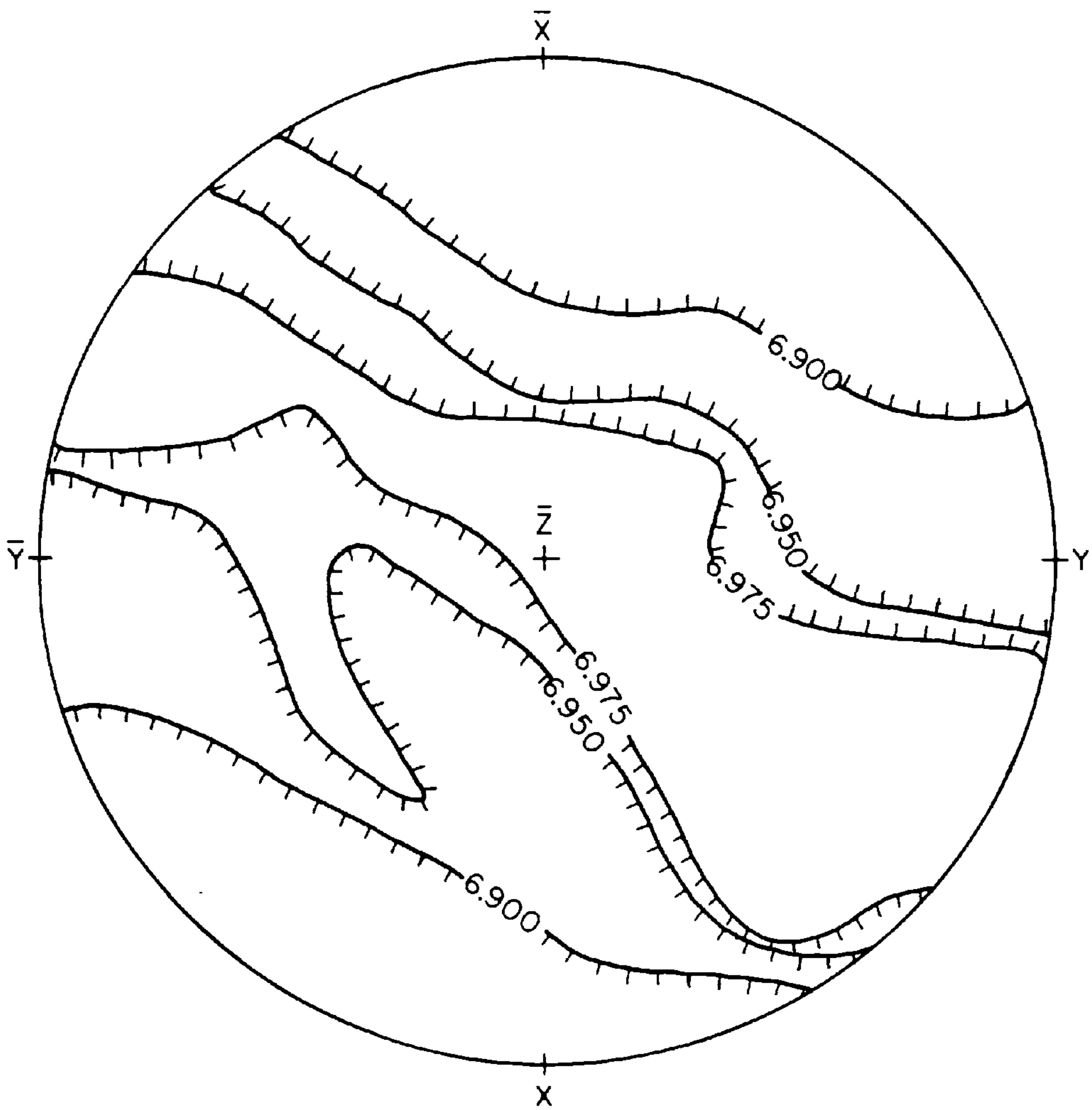


FIGURE 6. - Equal area projection of sonic pulse velocity (km/sec) for Dresser basalt.

Holston Limestone

Geologic Occurrence

The Holston formation, with other lithologically similar rocks, is found in a series of northeastward trending belts several hundred feet wide and tens of miles long in the Great Valley of east Tennessee (7). The active quarries are centered in the Knoxville area.

The Holston formation is known by the trade name of Tennessee marble because it meets or exceeds the ornamental and construction requirements of a marble. It is, however, an essentially unmetamorphosed, coarsely crystalline limestone of Middle Ordovician age. The formation shows a range of colors from light gray to pinks and red to dark brown. Dark gray stylolitic seams are characteristic features, and often separate one color from another.

The whole formation is about 400 ft thick, but seldom is more than 75 ft quarryable because of folding, faulting, and erosion. The dip is gentle to overturned (4).

The Holston Limestone was deposited as a "fossil hash," consisting of shells and shell fragments. After their deposition, the beds were buried, compacted, and lithified. Later tectonic activity was not only responsible for folding, faulting, and regional uplifts, but also for partial recrystallization to a fabric of twinned calcite grains that enclose and replace fossil fragments.

Properties

The petrographic description, thin-section photographs, and core surface photograph are shown in figure 7. The equal area plot of the acoustic velocity is shown in figure 8. Holston Limestone has a transversely isotropic elastic symmetry with 2.9 pct velocity anisotropy. The low value elastic axis is perpendicular to the orientation arrow and in the horizontal plane. The in situ orientation of this unique axis is in the east-west direction. The planes of isotropy are vertical and north in direction.

Table 5 gives the physical property, static, and dynamic test results.

TABLE 5. - Holston Limestone test results

Property[1]	Block No. 1		Block No. 13		Block No. 40		Composite	
	Mean	CV[2]	Mean	CV[2]	Mean	CV[2]	Mean	CV[2]
Porosity.....................pct..	0.24	20.0	0.17	26.0	0.11	57.4	0.17	43.4
Permeability..............µm/sec..	([3])	-	([3])	-	([3])	-	([3])	-
Density...................g/cm^3..	2.70	0.0	2.70	0.0	2.70	0.0	2.70	0.1
Shore hardness....................	56.4	3.9	57.9	3.0	60.8	1.8	58.4	4.3
Compressive strength.......MN/m^2..	119	3.16	116	5.79	119	2.40	118	4.1
Do.................10^3 psi..	17.2	3.16	16.8	5.79	17.3	2.40	17.1	4.1
Compressive Young's modulus GN/m^2..	61.2	8.59	61.3	9.02	64.0	3.93	62.2	7.5
Do.................10^6 psi..	8.88	8.59	8.89	9.02	9.28	3.93	9.02	7.5
Tensile strength...........MN/m^2..	10.1	14.7	8.08	28.1	11.9	20.4	10.1	25.6
Do.................10^3 psi..	1.47	14.7	1.18	28.1	1.67	20.4	1.45	25.6
Tensile Young's modulus....GN/m^2..	79.0	5.40	70.3	20.1	71.0	24.5	73.3	18.1
Do.................10^6 psi..	11.4	5.40	10.2	20.1	10.3	24.5	10.6	18.1
Pulse velocity............km/sec..	6.46	0.2	6.45	0.1	6.42	0.2	6.44	0.4
Bar velocity..............km/sec..	5.43	0.2	5.41	0.1	5.41	0.1	5.42	0.2
Torsional velocity........km/sec..	3.36	0.0	3.35	0.0	3.35	0.1	3.35	0.1
Dynamic Young's modulus[4]...GN/m^2..	79.7	0.4	79.1	0.2	79.1	0.3	79.3	0.5
Dynamic shear modulus[4].....GN/m^2..	30.4	0.2	30.4	0.1	30.3	0.3	30.4	0.3
Poisson's ratio[4].................	0.317	0.4	0.317	0.3	0.315	0.4	0.316	0.5

[1]Specimen prepared with the long axis perpendicular to the top face (along Z-axis).
[2]Coefficient of variation, percent.
[3]Less than 1×10^{-4} µm/sec.
[4]Calculation is based on the assumption of isotropy.

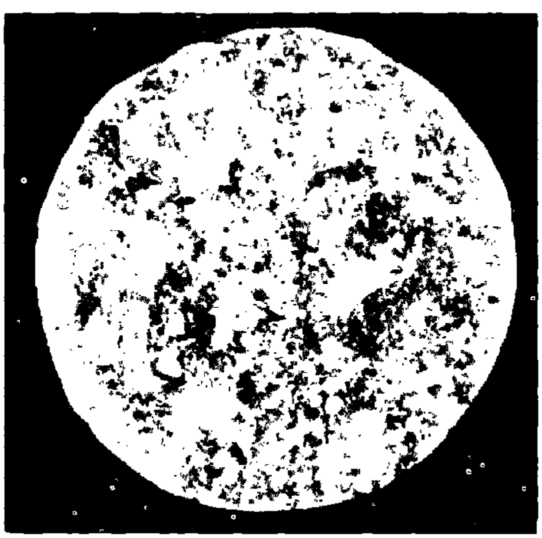
HOLSTON LIMESTONE
Thin section photographs

Thin section at crossed nicols

Thin section plane polarized

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Scale, mm



3/4-inch-diameter core

No. 3-IT

Holston Limestone

Color: Pink

Texture: Massive, crystalline, twinned crystals of calcite surround bioclastic calcite. Opaque matter is disseminated throughout the fossiliferous calcite.

Phases:	Bioclastic	- 70.0 pct
	Crystalline calcite	- 29+ pct
	Opaque matter	- 1.0 pct

Classification: Bioclastic limestone

FIGURE 7. - Petrographic description of Holston Limestone.

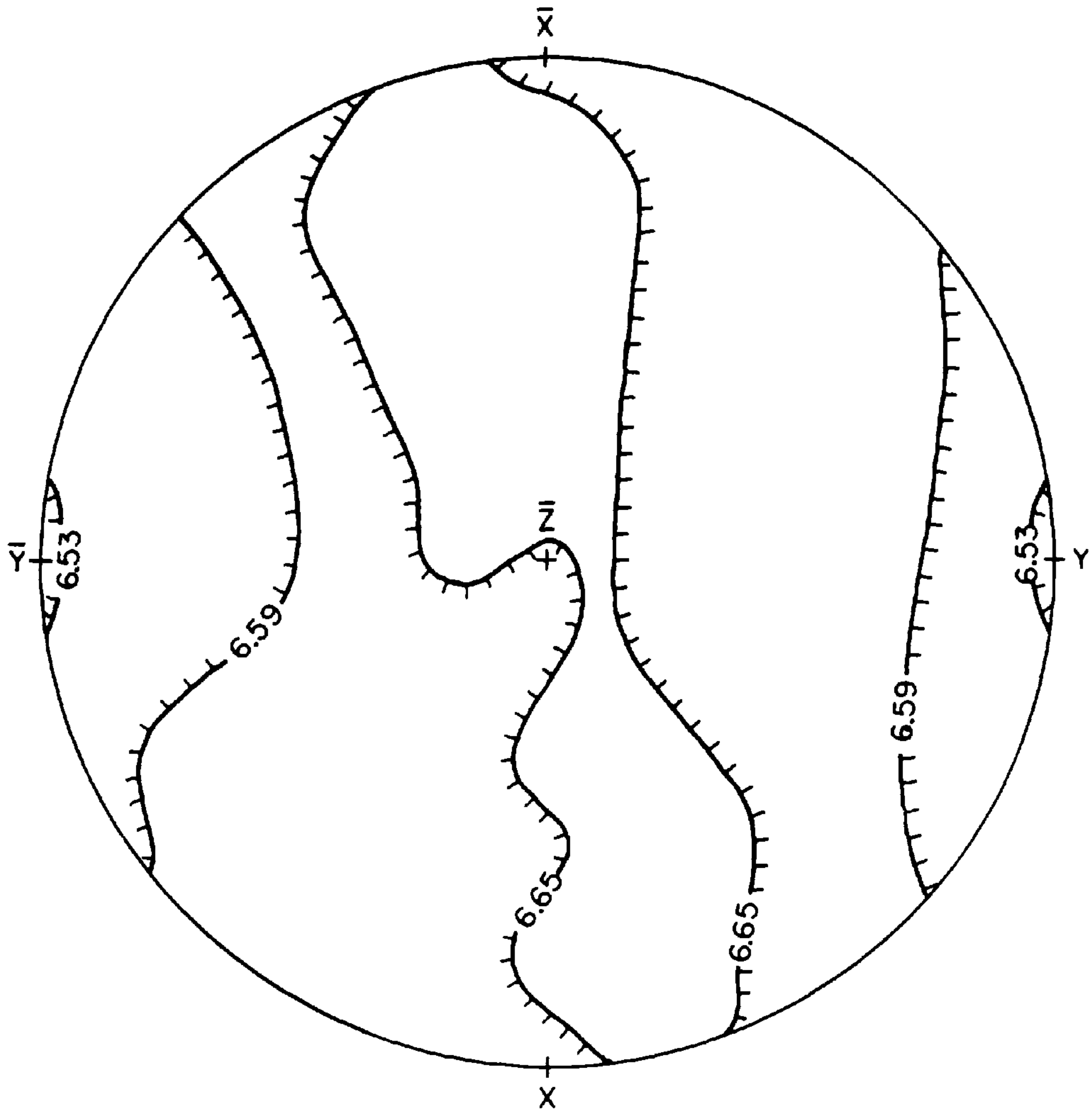


FIGURE 8. - Equal area projection of sonic pulse velocity (km/sec) for Holston Limestone.

Salem Limestone

Geologic Occurrence

Although such names as Salem, Spergen, Indiana, and Bedford have all been applied to limestone from which the Bedford, Inc., building stone is obtained, Salem is the name preferred by the U.S. and Indiana Geological Surveys (14).

Salem is a flat-lying Mississippian age limestone which underlies the St. Louis Limestone and in Indiana overlies the Harrodsburg Limestone. In Indiana, Salem is typically massive and lenticular, attaining thicknesses of 50 to 60 ft but locally pinching out. Layers of buff to nearly black bituminous calcareous shale are associated with the massive limestone, especially at the top and bottom. Including these layers, the formation has a maximum thickness of 90 to 100 ft.

Salem Limestone is a distinctive rock type which may be called a microquina and has even been referred to as a spergenite because of the abundance of fossils and fossil fragments. As the fossil shells accumulated, they were washed back and forth by waves, swept along by currents, and finally deposited as bars and shoals along a shoreline, grading seaward into a normally bedded limestone. Megascopically the fossil remains resemble clean winnowed sand. After its burial, the calcareous sand was cemented by crystalline calcite (4).

Properties

The petrographic description, thin-section photographs, and core surface photograph are shown in figure 9. The equal area plot of the acoustic velocity is shown in figure 10. Salem Limestone has an orthotropic elastic symmetry with 2.9 pct velocity anisotropy. The low value elastic axis is vertical and hence perpendicular to bedding. The high value elastic axis is 45° to the right of the orientation arrow and the intermediate value axis is 45° to the left of the arrow. The geographic orientation is unknown.

Table 6 gives the physical property, static, and dynamic test results.

TABLE 6. - Salem Limestone test results

Property[1]	Block No. 1		Block No. 10		Block No. 40		Composite	
	Mean	CV[2]	Mean	CV[2]	Mean	CV[2]	Mean	CV[2]
Porosity....................pct..	12.0	4.7	12.8	3.9	12.6	1.6	12.5	4.4
Permeability..............μm/sec..	0.007	17.5	0.008	17.5	0.008	18.9	0.008	18.6
Density...................g/cm^3..	2.34	0.2	2.34	0.2	2.33	0.2	2.34	0.2
Shore hardness....................	28.0	6.0	26.4	6.5	25.9	12.4	58.4	4.3
Compressive strength.......MN/m^2..	40.6	4.8	38.1	7.2	53.0	21.0	43.9	21.1
Do.................10^3 psi..	5.89	4.8	5.53	7.2	7.69	21.0	6.37	21.1
Compressive Young's modulus GN/m^2..	19.4	20.1	17.0	20.5	39.3	47.9	25.2	59.0
Do.................10^6 psi..	2.81	20.1	2.47	20.5	5.69	47.9	3.66	59.0
Tensile strength..........MN/m^2..	5.26	24.9	5.24	17.3	5.19	12.5	5.23	18.1
Do.................10^3 psi..	0.77	24.9	0.76	17.3	0.76	12.5	0.759	18.1
Tensile Young's modulus....GN/m^2..	30.8	32.7	30.4	14.2	29.2	16.7	30.0	20.9
Do.................10^6 psi..	4.47	32.7	4.40	14.2	4.23	16.7	4.35	20.9
Pulse velocity............km/sec..	4.49	0.9	4.51	0.7	4.54	0.7	4.51	0.9
Bar velocity..............km/sec..	4.02	1.0	4.03	0.8	4.04	1.2	4.03	1.0
Torsional velocity........km/sec..	2.55	1.0	2.56	0.5	2.56	0.7	2.56	0.8
Dynamic Young's modulus[3]...GN/m^2..	37.8	2.3	37.9	1.7	38.1	2.4	37.9	2.1
Dynamic shear modulus[3].....GN/m^2..	15.2	2.4	15.3	1.3	15.4	1.5	15.3	1.8
Poisson's ratio[3].................	0.270	2.7	0.271	1.6	0.280	2.4	0.272	2.4

[1]Specimen prepared with the long axis perpendicular to the top face (along Z-axis).
[2]Coefficient of variation, percent.
[3]Calculation is based on the assumption of isotropy.

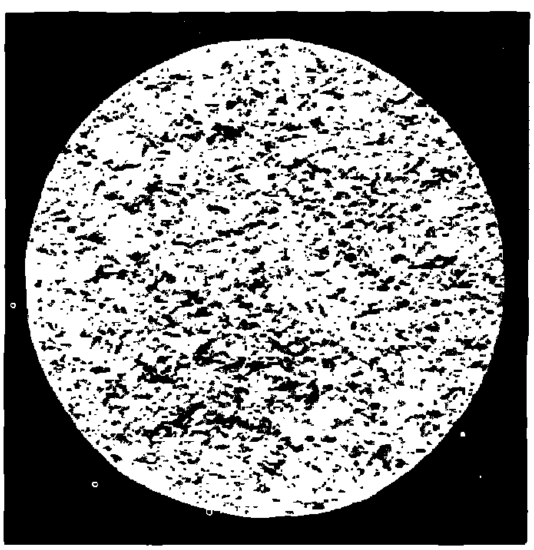
SALEM LIMESTONE
Thin section photographs

Thin section at crossed nicols

Thin section plane polarized

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Scale, mm



3/4-inch-diameter core

No. 3-1

Salem Limestone

Color: Light tan to brown

Texture: Bioclastic
Shells of gastropods, crinoid stems and calices are cemented together by crystalline calcite.

Phases: Bossiliferous calcite - 69.0 pct
Calcite cement - 31.0 pct

Classification: Brecciated limestone or coquina

FIGURE 9. - Petrographic description of Salem Limestone.

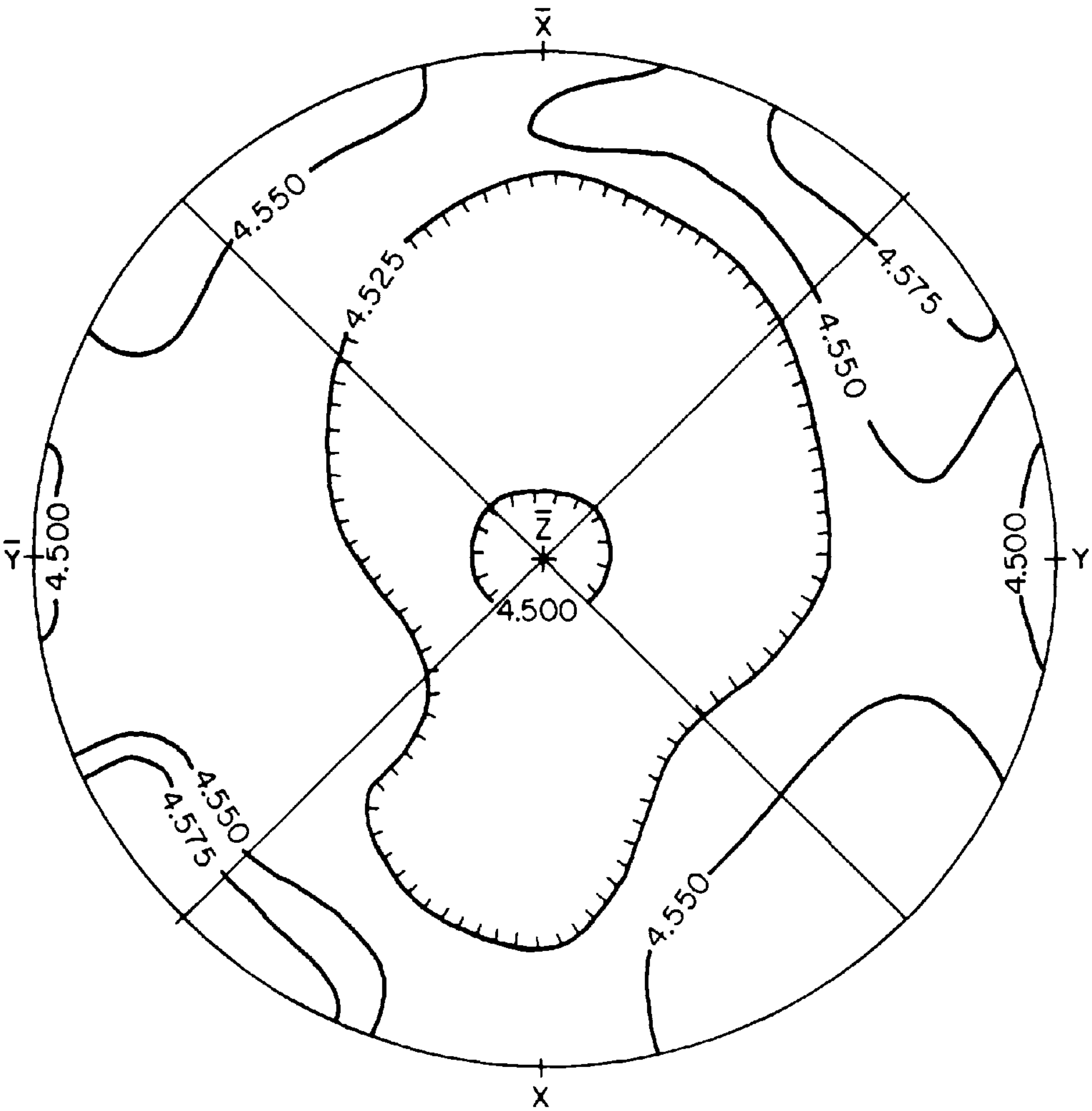


FIGURE 10. - Equal area projection of sonic pulse velocity (km/sec) for Salem Limestone.

Sioux Quartzite

Geologic Occurrence

Sioux Quartzite, known commercially as Jasper quartzite, is exposed and quarried in the southeastern corner of South Dakota and the southwestern corner of Minnesota. It is a sedimentary rock that consists predominantly of pink-coated, fine grains of quartz sand cemented to a nonporous quartzite by silica. Since both the grains and cement are made of silica, the rock is homogeneous, tough, hard, and pure.

Sioux Quartzite evidently accumulated as a series of water-laid sands that were deposited near the shore of an ancient shallow sea or large lake. The evenness of grain size and the absence of anything but quartz grains indicate that the material was worked for a long time by water before being covered by more sand. The presence of ripple marks and cross bedding indicate that the transporting currents were strong, and the presence of mudcracks suggest an environment of alternating air and water exposure typical of a tidal flat or other shore zone.

The sediments are laterally extensive and have been gently warped, tilted, and jointed at some period in the past. The formation is estimated to be more than 3,000 ft thick, and from data available, appears to be an east-west trending syncline or group of synclines. Usually there are three sets of well developed, primarily vertical joints striking N 75°-45° W, N 10°-15° W, and N 55°-70° E; in some exposure, however, there is no discernible pattern to jointing or direction of jointing (3).

The age of Sioux Quartzite cannot be determined directly by its relationship to other formations, because it is obscured by glacial overburden and no fossils are present. From evidence available the formation is Lower Ordovician or older and most writers feel that it is upper Precambrian.

Properties

The petrographic description, thin-section photographs, and core surface photograph are shown in figure 11. The equal area plot of the acoustic velocity is shown in figure 12. Sioux Quartzite has an orthotropic elastic symmetry and 9.6 pct velocity anisotropy. The low value elastic axis is vertical and perpendicular to the bedding. A high value elastic axis is oriented N 25° E in the horizontal plane. This is 25° to the right of the orientation arrow. The intermediate elastic axis is difficult to establish with certainty but is probably N 65° W and in the horizontal plane.

Table 7 gives the physical property, static, and dynamic test results.

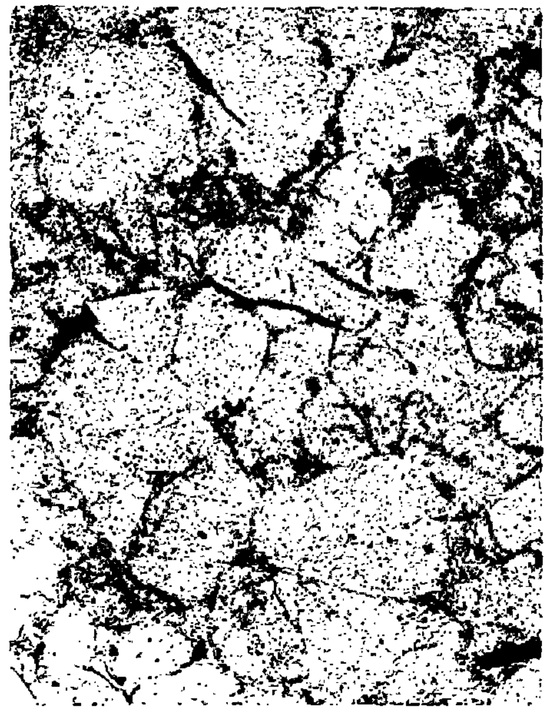
TABLE 7. - Sioux Quartzite test results

Property[1]	Block No. 12		Block No. 16		Block No. 35		Composite	
	Mean	CV[2]	Mean	CV[2]	Mean	CV[2]	Mean	CV[2]
Porosity......................pct..	0.15	34.3	0.15	34.6	0.13	62.4	0.14	37.9
Permeability..............µm/sec..	([3])	-	([3])	-	([3])	-	([3])	-
Density...................g/cm³..	2.64	0.0	2.64	0.0	2.64	0.0	2.64	0.1
Shore hardness...................	102.4	3.0	100.9	2.2	101.2	1.8	101	2.4
Compressive strength.......MN/m²..	512	10.2	511	8.54	492	7.38	505	8.7
Do.................10³ psi..	74.3	10.2	74.1	8.54	71.3	7.38	73.2	8.7
Compressive Young's modulus GN/m²..	50.2	3.60	59.8	8.68	59.2	1.74	56.4	8.2
Do.................10⁶ psi..	7.28	3.60	1.59	8.68	8.59	1.74	8.18	8.2
Tensile strength...........MN/m²..	10.2	9.08	11.0	12.6	11.4	27.3	10.8	18.1
Do.................10³ psi..	1.49	9.08	1.60	12.6	1.64	27.3	1.57	18.1
Tensile Young's modulus....GN/m²..	25.1	27.5	31.3	18.2	26.8	23.0	27.9	23.7
Do.................10⁶ psi..	3.30	27.5	4.54	18.2	3.89	23.0	4.05	23.7
Pulse velocity............km/sec..	4.74	2.0	4.80	3.4	4.72	2.5	4.75	2.8
Bar velocity..............km/sec..	4.65	1.5	4.68	3.8	4.59	2.9	4.63	3.5
Torsional velocity........km/sec..	3.43	1.1	3.46	2.7	3.41	2.0	3.43	2.1
Dynamic Young's modulus[4]...GN/m²..	57.0	3.1	57.8	7.6	55.5	5.9	56.8	6.0
Dynamic shear modulus[4].....GN/m²..	31.0	2.3	31.6	5.5	30.6	4.0	31.1	4.3
Poisson's ratio[4]..................	0.119	35.0	0.143	16.4	0.153	12.3	0.138	23.3

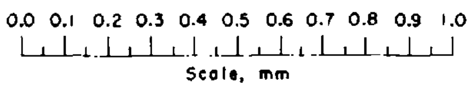
[1]Specimen prepared with the long axis perpendicular to the top face (along Z-axis).
[2]Coefficient of variation, percent.
[3]Less than 1×10^{-4} µm/sec.
[4]Calculation is based on the assumption of isotropy.

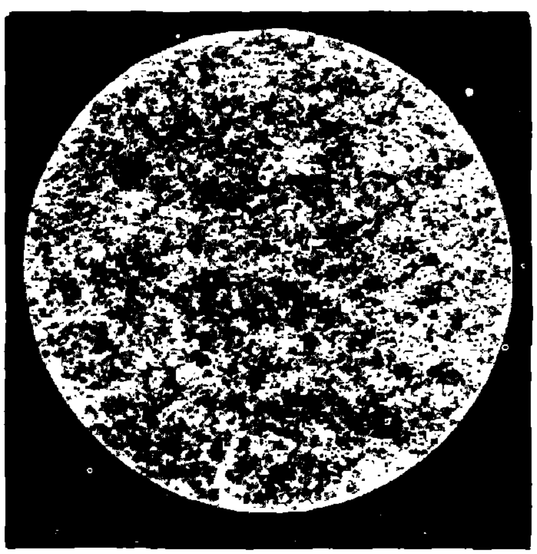
SIOUX QUARTZITE
Thin section photographs

Thin section at crossed nicols



Thin section plane polarized





3/4-inch-diameter core

No. 3-35

Sioux Quartzite

Color: Grayish pink

Texture: Massive and granular with angular to subrounded sand-size quartz grains. The quartz grains are very tightly packed and cemented with quartz. Therefore, there is very little pore space.

Phases: Quartz – 99+ pct
Hematite
Magnetite
Zircon
Rutile
Amphibole

Classification: Quartzite

FIGURE 11. - Petrographic description of Sioux Quartzite.

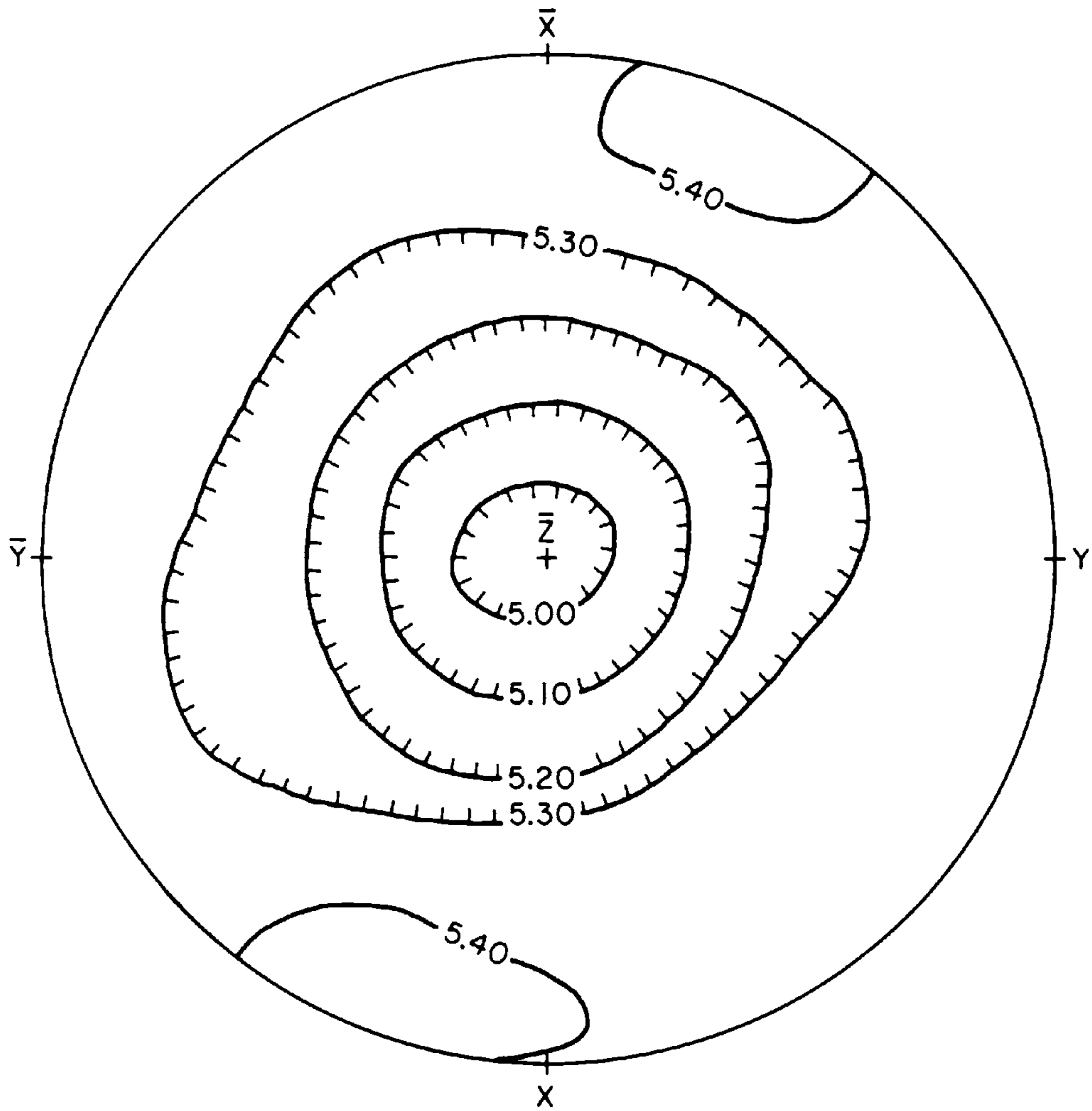


FIGURE 12. - Equal area projection of sonic pulse velocity (km/sec) for Sioux Quartzite.

St. Cloud Gray Granodiorite

Geologic Occurrence

In the area of St. Cloud, in central Minnesota, are exposed scattered knobs and low hills of unweathered igneous rock of Precambrian age from which the thin covering of glacial till has been removed by erosion (4). There are 16 different igneous rock types ranging from norite to granite. Three main color varieties of granite are quarried in this area: pink, red, and gray. The gray variety has the geological name of St. Cloud Gray Granodiorite and the trade name of Charcoal granite.

St. Cloud Gray Granodiorite, of late algoman age, is massive but not homogeneous. Exposures are dotted with small dark inclusions and cut by numerous basalt, aplite, and diabase dikes and veins ranging in width from less than 1 inch to 6 to 8 ft. The dikes and veins twist and branch irregularly and in some places form a network. In some areas, the St. Cloud Gray Granodiorite is irregularly altered to a pink color, owing to granitization caused by the later intrusion of the St. Cloud Red Granite (15). Spaced joints, striking east-west and dipping steeply north, are well developed, but sheet structure is poor or absent.

The central Minnesota area consists of a country rock (Thomson formation) of schist which has been invaded by intrusives on three separate occasions. During early algoman time, the Thomson formation was metamorphosed from interbedded slate and graywacke to schist and intruded by granite gneiss. In the late algoman period, the region was invaded by five related magma injections of which the St. Cloud Gray Granodiorite appears to have been second. In the middle Keweenawan, the region was intruded for a third time by granitic magmas and finally by basalt dikes.

Properties

The petrographic description, thin-section photographs, and core surface photograph are shown in figure 13. The equal area plot of the acoustic velocity is shown in figure 14. St. Cloud Gray Granodiorite has a transversely isotropic to weakly orthotropic elastic symmetry with 7.3 pct velocity anisotropy. The low value elastic axis is vertical with an indication of a high value elastic axis 90° to the orientation arrow marked on the rock cubes and in the horizontal plane. The arrow indicates the in situ north direction. The rift in this quarry is in the horizontal plane.

Table 8 gives the physical property, static, and dynamic test results.

TABLE 8. - St. Cloud Gray Granodiorite test results

Property[1]	Block No. 6		Block No. 21		Block No. 37		Composite	
	Mean	CV[2]	Mean	CV[2]	Mean	CV[2]	Mean	CV[2]
Porosity.....................pct..	0.07	42.9	0.10	43.6	0.07	96.4	0.08	61.2
Permeability..............μm/sec..	([3])	-	([3])	-	([3])	-	([3])	-
Density....................g/cm³..	2.72	0.0	2.72	0.1	2.71	0.0	2.72	0.1
Shore hardness....................	99.1	3.0	100.2	4.1	100.0	3.6	99.8	3.5
Compressive strength.......MN/m²..	280	3.0	282	1.8	284	3.0	282	2.2
Do.................10³ psi..	40.6	3.0	41.0	1.8	41.3	3.0	40.9	2.2
Compressive Young's modulus GN/m²..	63.5	1.2	78.6	2.3	70.2	2.5	70.8	9.1
Do.................10⁶ psi..	9.21	1.2	11.4	2.3	10.2	2.5	10.3	9.1
Tensile strength...........MN/m²..	6.90	5.35	6.28	10.3	7.72	13.6	6.97	13.8
Do.................10³ psi..	1.0	5.35	0.91	10.3	1.12	13.6	1.01	13.8
Tensile Young's modulus....GN/m²..	28.9	8.20	24.5	19.0	38.5	12.6	30.0	24.1
Do.................10⁶ psi..	4.19	8.20	3.56	19.0	5.59	12.6	4.35	24.1
Pulse velocity............km/sec..	4.46	0.6	4.46	0.7	4.88	1.4	4.60	4.5
Bar velocity..............km/sec..	4.10	0.8	4.05	0.9	4.50	1.7	4.21	5.1
Torsional velocity........km/sec..	2.92	0.3	2.92	0.5	3.05	0.8	2.96	2.3
Dynamic Young's modulus[4]...GN/m²..	45.6	1.7	44.5	1.8	55.0	3.4	48.4	10.2
Dynamic shear modulus[4].....GN/m²..	23.2	0.7	23.1	1.0	25.3	1.7	23.9	4.5
Poisson's ratio[4]..................	0.244	2.6	0.255	2.7	0.238	2.7	0.245	4.0

[1]Specimen prepared with the long axis perpendicular to the top face (along Z-axis).
[2]Coefficient of variation, percent.
[3]Less than 1 x 10^{-4} μm/sec.
[4]Calculation is based on the assumption of isotropy.

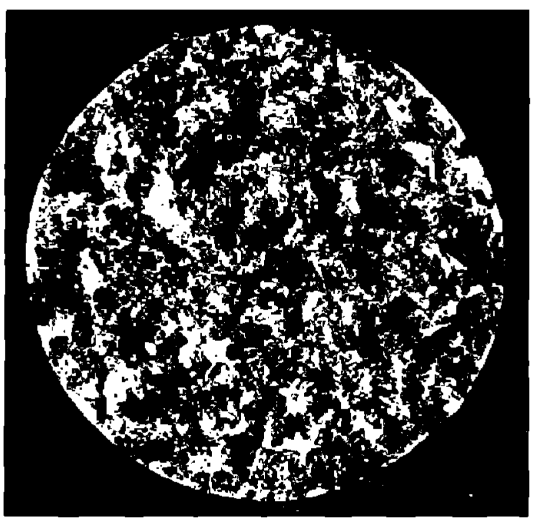
ST. CLOUD GRAY GRANODIORITE
Thin section photographs

Thin section at crossed nicols

Thin section plane polarized

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Scale, mm



3/4-inch-diameter core

No. 3-37

St. Cloud Gray Granodiorite

Color: Gray

Texture: Massive, crystalline, medium grained

Phases:

Quartz	- 16.7 pct
Microcline	- 20.0 pct
Plagioclase	- 40.8 pct
Biotite-chlorite	- 9.5 pct
Hornblende	- 11.7 pct
Magnetite	- 1.2 pct
Rutile-apatite	- 0.1 pct

Classification: Granodiorite

FIGURE 13. - Petrographic description of St. Cloud Gray Granodiorite.

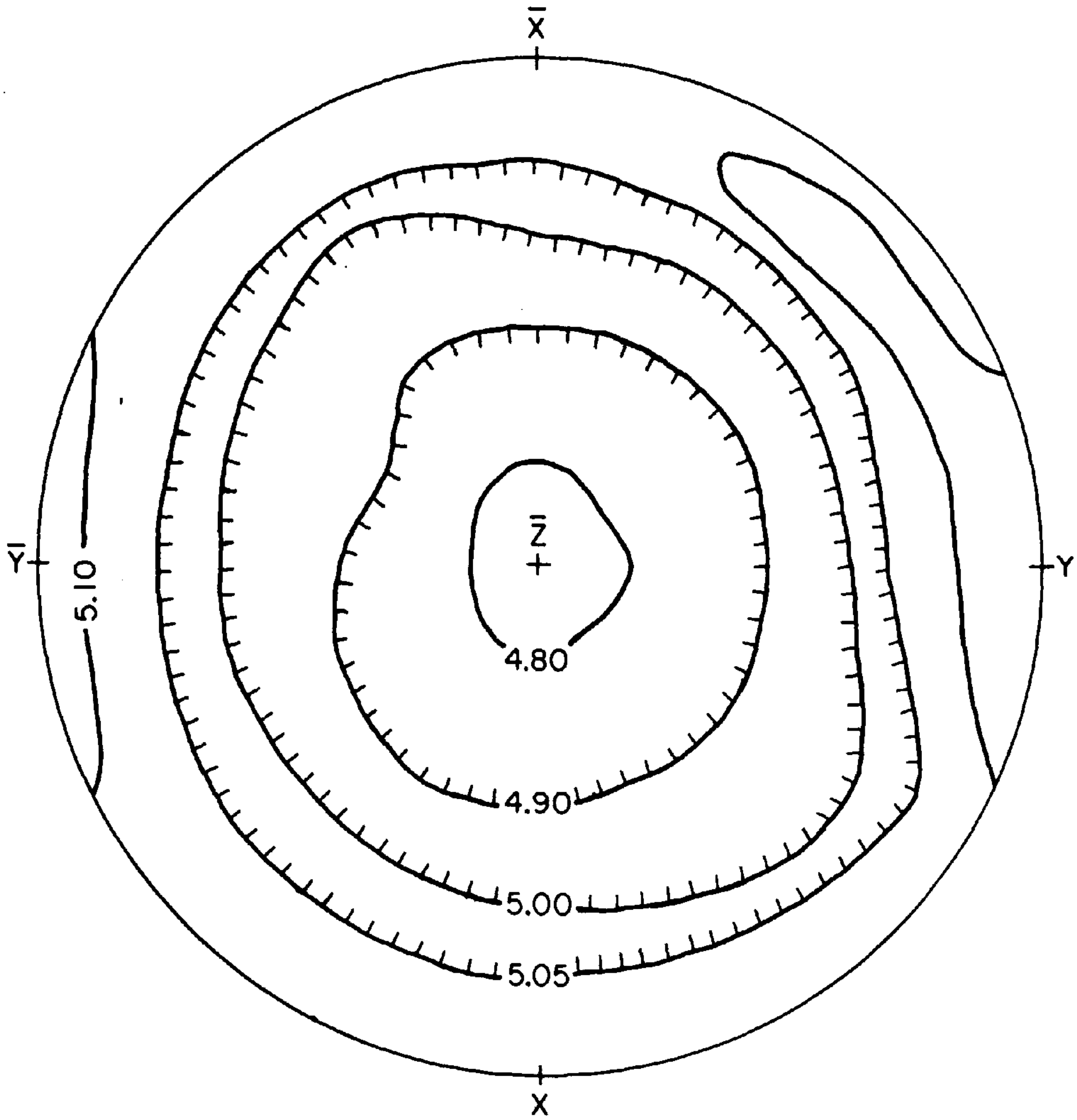


FIGURE 14. - Equal area projection of sonic pulse velocity (km/sec) for St. Cloud Gray Granodiorite.

Westerly Granite

Geologic Occurrence

Westerly Granite and associated pegmatites intrude folded Pennsylvanian sedimentary rocks along the southwestern shore of Narragansett Bay. Evidence found in Connecticut indicates that Westerly Granite is older than Triassic, making it Late Pennsylvanian or Permian in age. Westerly Granite is found chiefly in the southwest corner of Rhode Island where it was quarried in and near the town of Westerly, and extends into the southwest corner of Connecticut (10).

Westerly Granite includes many small pegmatites and medium-grained and fine-grained rocks ranging in composition from that of a granite to that of a granodiorite. The fine-grained Westerly Granites were intruded as dikes into the older granite gneisses which form extensive parts of the surface along the Atlantic shore. These granite gneisses were originally granites which had also been intruded into earlier gneisses of metamorphosed sedimentary rock, of which none remains today at Westerly. The granites themselves were later intruded by pegmatite dikes and still later by basic dikes.

The quarry from which the ARPA block was taken lies in a dikelike mass about 100 ft thick dipping 45° south. Two sets of almost vertical joints strike N 25° E and N 45° W and a rift dips 20° in an easterly direction.

Properties

The petrographic description, thin-section photographs, and core surface photograph are shown in figure 15. The equal area plot of the acoustic velocity is shown in figure 16. Westerly Granite has an orthotropic elastic symmetry with 10 pct velocity anisotropy. The intermediate elastic axis is in the in situ up direction. The high value elastic axis is 45° to the left of the orientation arrow and the low value axis 45° to the right of the orientation arrow. These directions correspond to in situ directions of N 45° W and N 45° E respectively.

Table 9 gives the physical property, static, and dynamic test results.

TABLE 9. - Westerly Granite test results

Property[1]	Block No. 3A		Block No. 5C		Block No. 7E		Composite	
	Mean	CV[2]	Mean	CV[2]	Mean	CV[2]	Mean	CV[2]
Porosity....................pct..	0.34	84.2	0.57	97.2	0.16	47.9	0.35	101.0
Permeability.............µm/sec..	(3)	-	(3)	-	(3)	-	(3)	-
Density....................g/cm^3..	2.64	0.0	2.64	0.0	2.64	0.0	2.64	0.1
Shore hardness....................	93.8	3.1	92.4	2.1	94.2	3.6	93.8	2.9
Compressive strength.......MN/m^2..	277	4.68	247	3.51	225	10.9	233	8.0
Do.................10^3 psi..	32.9	4.68	35.8	3.51	32.7	10.9	33.8	8.0
Compressive Young's modulus GN/m^2..	46.7	16.2	54.2	4.02	48.9	20.0	49.9	15.4
Do.................10^6 psi..	6.77	16.2	7.86	4.02	7.10	20.0	7.2	15.4
Tensile strength..........MN/m^2..	8.56	6.97	9.63	8.20	10.5	6.57	9.61	11.1
Do.................10^3 psi..	1.24	6.97	1.40	8.20	1.53	6.57	1.39	11.1
Tensile Young's modulus....GN/m^2..	13.9	12.8	19.2	19.6	24.8	14.5	19.6	28.3
Do.................10^6 psi..	2.02	12.8	2.79	19.6	3.27	14.5	2.83	28.3
Pulse velocity............km/sec..	3.98	1.0	4.43	1.5	4.63	2.6	4.35	6.6
Bar velocity..............km/sec..	3.71	1.0	4.17	1.7	4.39	2.4	4.09	7.2
Torsional velocity........km/sec..	2.51	0.9	2.74	1.1	2.87	2.2	2.71	5.9
Dynamic Young's modulus[4]...GN/m^2..	36.3	2.0	45.8	3.4	50.8	4.8	44.3	14.3
Dynamic shear modulus[4].....GN/m^2..	16.6	1.9	19.8	2.3	21.8	4.3	19.4	11.7
Poisson's ratio[4].................	0.226	2.7	0.212	2.6	0.202	4.7	0.213	5.6

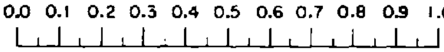
[1]Specimen prepared with the long axis perpendicular to the top face (along Z-axis).
[2]Coefficient of variation, percent.
[3]Less than 1×10^{-4} µm/sec.
[4]Calculation is based on the assumption of isotropy.

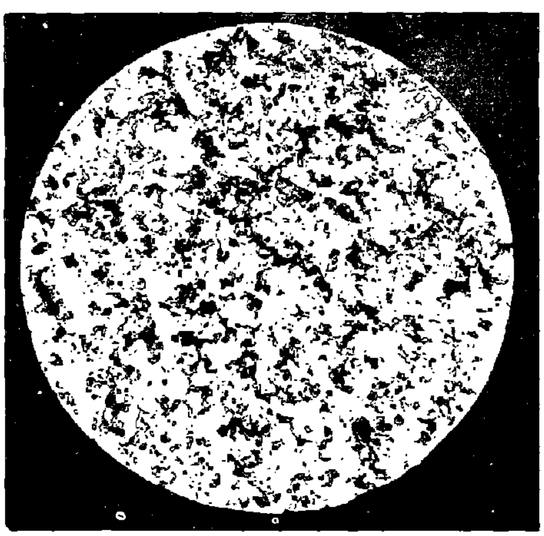
WESTERLY GRANITE

Thin section photographs

Thin section at crossed nicols

Thin section plane polarized





3/4-inch-diameter core

No. 3-2A

Westerly Granite

Color: Light gray

Texture: Massive, fine-grained, equi-granular

Phases:		
	Plagioclase	- 43.0 pct
	Microcline	- 22.0 pct
	Quartz	- 24.6 pct
	Biotite	- 6.9 pct
	Muscovite	- 2.0 pct
	Zircon	- 1.0 pct
	Magnetite	- 0.9 pct

Classification: Granodiorite

FIGURE 15. - Petrographic description of Westerly Granite.

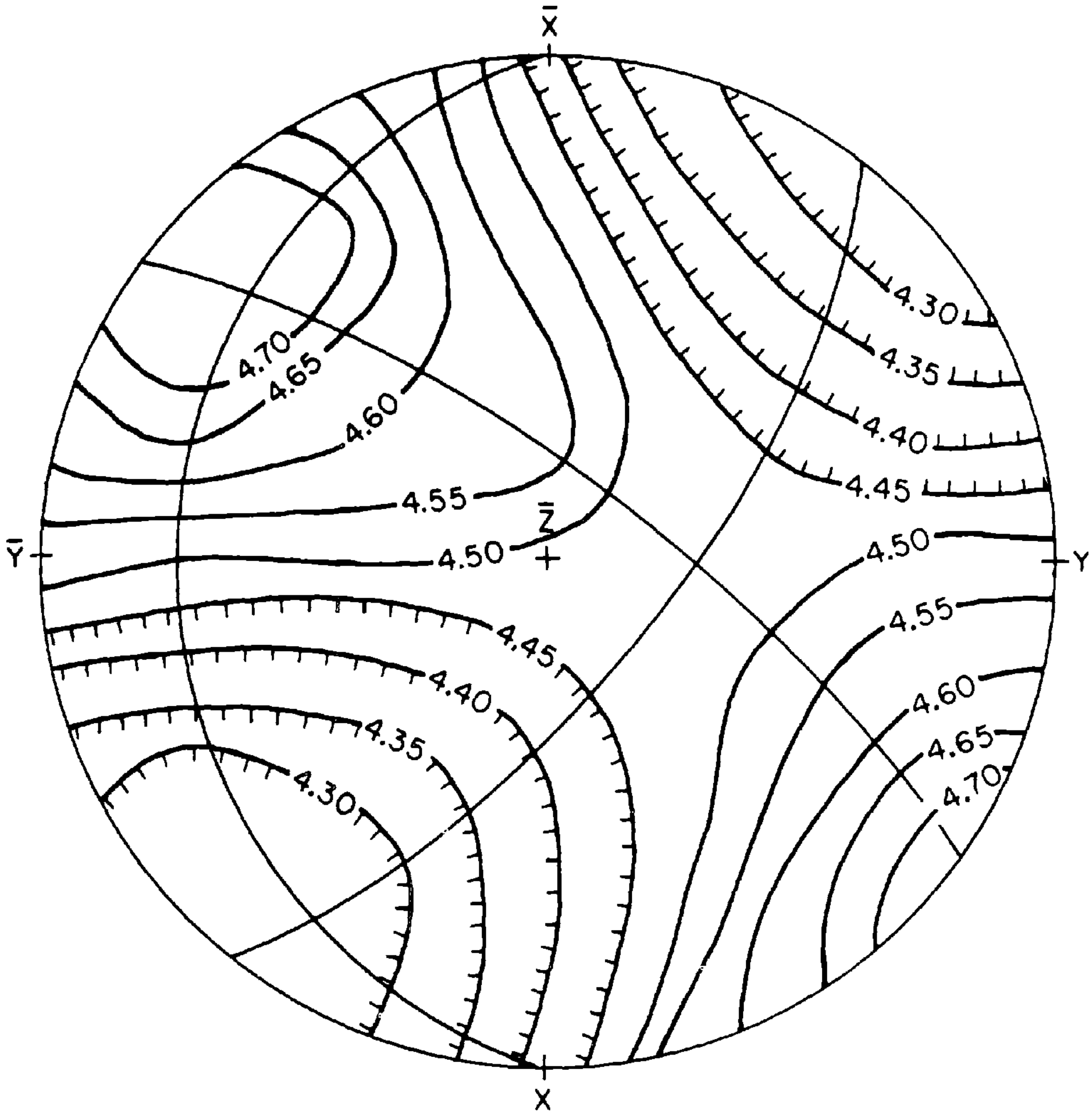


FIGURE 16. - Equal area projection of sonic pulse velocity (km/sec) for Westerly Granite.

SUMMARY

A suite of eight rock types has been established under the ARPA Rock Mechanics and Rapid Excavation program for use by various groups doing specialized research in rock mechanics. Physical and mechanical property test results and a short geologic sketch are presented for each rock type. As evidenced by coefficient of variation comparisons, most of the rock blocks were as homogeneous as the individual 1-ft cubes comprising the block. Salem Limestone showed rather large compressive property variations within and between the cubes tested. Care should be exercised during further use of that rock. A limited amount of rock cubes are available from the Bureau of Mines Twin Cities Mining Research Center for use by researchers to broaden the information available on the suite.

REFERENCES

1. American Society for Testing and Materials. Standard Method of Test for Direct Tensile Strength of Rock Core Specimens. D2936-71 in 1972 Annual Book of ASTM Standards: Part 11, Bituminous Materials for Highway Construction, Waterproofing, and Roofing; Soils; Peats, Mosses, and Humus; Skid Resistance. Philadelphia, Pa., 1972, pp. 909-911.

2. _____. Standard Method of Test for Triaxial Compressive Strength of Undrained Rock Core Specimens Without Pore Pressure Measurements. D2664-67 in 1972 Annual Book of ASTM Standards: Part 11, Bituminous Soils; Peats, Mosses, and Humus; Skid Resistance. Philadelphia, Pa., 1972, pp. 829-833.

3. Baldwin, B. A Preliminary Report on the Sioux Quartzite. S. Dak. Geol. Survey RI 63, 1949, pp. 1-25.

4. Bates, R. L. Geology of the Industrial Rocks and Minerals. Harper & Row, New York, 1960, 441 pp.

5. Bur, T. R., R. E. Thill, and K. E. Hjelmstad. An Ultrasonic Method for Determining the Elastic Symmetry of Materials. BuMines RI 7333, 1969, 23 pp.

6. Lewis, W. E., and S. Tandanand. Bureau of Mines Test Procedures for Rocks. BuMines IC 8628, 1974.

7. Maher, S. W., and J. P. Walters. The Marble Industry of Tennessee. Tenn. Dept. Conservation and Commerce IC No. 9, 1960, pp. 7-10.

8. Marshall, L. G. Coyote-Hole Primary Blasting, Dresser Trap Rock Company, Dresser, Wisconsin. BuMines IC 7913, 1959, pp. 1-5.

9. Murthy, V. R. Bedrock Geology of the East Barre Area, Vermont. Vermont Geol. Survey Bull., No. 10, 1957, pp. 11-113.

10. Quinn, A. W. Bedrock Geology of Rhode Island. Trans., N.Y. Acad. Sci., 1954, pp. 264-269.

11. Thiel, E. Correlation of Gravity Anomalies With the Keweenawan Geology of Wisconsin and Minnesota. Bull. Geol. Soc. Am., v. 67, 1956, pp. 1079-1100.

12. Thill, R. E., J. R. McWilliams, and T. R. Bur. An Acoustical Bench for an Ultrasonic Pulse System. BuMines RI 7164, 1968, 22 pp.

13. Vickers, B. L., and R. E. Thill. A New Technique for Preparing Rock Spheres. J. Sci. Instr., Series 2, v. 2, 1969, pp. 901-902.

14. Willer, J. M., and A. H. Sutton. Mississippian Border of the Eastern Interior Basin. Bull. Am. Assoc. Petrol. Geol., v. 24, No. 5, 1940, pp. 766-858.

15. Woyski, M. S. Intrusives of Central Minnesota. Bull. Geol. Soc. Am., v. 60, 1949, pp. 999-1016.

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