ENGINEERING GEOLOGY, STRESS REGIME AND MECHANICAL

PROPERTIES OF SOME PRECAMBRIAN ROCKS

IN SOUTH CENTRAL WISCONSIN

by

B. C. Haimson

ABSTRACT

In conjunction with a preliminary investigation toward the construction of a large underground cavern system for energy storage we have conducted extensive engineering geology - rock mechanics studies in some of the Precambrian rock of south-central Wisconsin. These studies included surface rock and joint reconnaissance and seismic refraction measurements, drilling and coring of exploration boreholes at Montello and Waterloo and subsequent core studies, ground stress measurements, and testing of rock mechanical properties. The results of this investigation are the subject of this contribution.

INTRODUCTION

At the University of Wisconsin-Madison, we are engaged in a geological engineering-rock mechanics site investigation within the State of Wisconsin leading to the design of a hard rock cavern system which will house superconductive magnets for electric energy storage. Such magnets can be charged with electric current during low consumption periods, and discharged again when the demand peaks. They are similar in principle to and competitive with pumped storage but are superior in efficiency and free from topographic constraints (WSESP, 1974, 1976, 1977).

The unique geotechnical features of superconductive magnet caverns are their annular shape, the high radial and axial loads applied to the cavern walls due to magnetically induced forces, the high stiffness rock requirements, and the strict dry tunnel conditions needed to maintain safe operation. Of special importance to the site investigation are knowledge of the state of stress in the rock to be excavated, the ground water regime, and the strength and deformability of the rock mass under both static and cyclic loadings. Due to strict constraints of strength, stiffness and permeability we have so far restricted the siting to Precambrian crystalline rock.

Our work has been concentrated on south-central Wisconsin which is in reasonable proximity to the population centers and power generating facilities. In south-central Wisconsin the Precambrian is buried under a few hundred feet of Paleozoic sediments and glacial drift. However, scattered exposures are located at Montello, Berlin, Baraboo, and Waterloo. These rocks fall into two groups: rhyolites and granophyric granites, and quartzites with interbedded phyllite and schists. The present contribution concerns itself with our surface and subsurface studies of the exposed rocks. Both field and laboratory measurements have been conducted and these will be described in the next sections.

---

[1]Department of Metallurgical and Mineral Engineering, University of Wisconsin-Madison, 1509 University Avenue, Madison, Wisconsin 53706

ENGINEERING GEOLOGY

Rock Description

Granites and Rhyolites

Red, medium-grained granite is exposed at Montello and Redgranite, Wisconsin. These rocks consist of quartz and perthite with minor hornblende and biotite in a complexly intergrown granophyric texture. Such a texture is generally considered evidence for a shallow depth of intrusion and accounts for the high strength that these rocks exhibit. The rhyolites are reddish-black and contain numerous features suggesting a volcanic origin, namely compositional banding, flow brecciation, flattened shards, and other microscopic features associated with volcanic ash flows (Asquith, 1964; Stark, 1930). The rhyolites possess foliation near Baraboo and at Berlin, Wisconsin, but elsewhere there is little evidence for recrystallization other than devitrification (Asquith, 1964). Phenocrysts of both quartz and feldspar are present in the rhyolites locally. Greenstone dikes having the composition of an augite andesite cut both the granites and the rhyolites, and coarse-grained rhyolite can be found cutting the rhyolite at Observatory Hill (Smith, 1978).

In the core obtained from a 215 m vertical borehole drilled in the Montello quarry we encountered red, medium-grained granite except for two greenstone dikes at 25-35 m and 85-96 m depth. The dikes were dipping 70°. Lithologically the rock was identical to that exposed on surface (Haimson, and others, 1976).

Age dates of 1800 m.y. B.P. for the granites and rhyolites (Van Schmus and others, 1975) and compositional similarities suggest a common magmatic origin for the two rocks. Indeed, it seems likely that granites were the sources of the volcanic rhyolites (Smith, 1978).

Baraboo and Waterloo Quartzites

The quartzite is a massive, vitreous rock comprised of more than 99% quartz in the form of thoroughly cemented medium to coarse sand-sized grains. It is generally pink, though some white to gray zones are found. Numerous argillaceous zones vary in thickness from a few inches to several feet; at Baraboo these rocks consist of phyrophyllite and quartz with minor hematite and muscovite, and at Waterloo they are muscovite bearing phyllites. Several brecciated zones are present in the Baraboo quartzite consisting of angular quartzite fragments in a quartz matrix (Dalziel and Dott, 1970). Stratigraphic thickness of the quartzite exceeds 1000 m. At Waterloo, the quartzite is cut by pegmatite dikes. Underlying the Baraboo quartzite are older dark rhyolites similar to those found elsewhere in southern Wisconsin. Radiometric age dates on the pegmatite and rhyolite are 1440 and 1800 m.y.B.P. respectively thus providing a range of possible ages for the quartzite (Aldrich and others) 1959; Van Schmus and others, 1975). Quartzites are known in the subsurface in the Fond du Lac area and over a circular area east of Waterloo (Fig. 1), suggesting that the Waterloo quartzite is part of a syncline similar to the Baraboo quartzite.

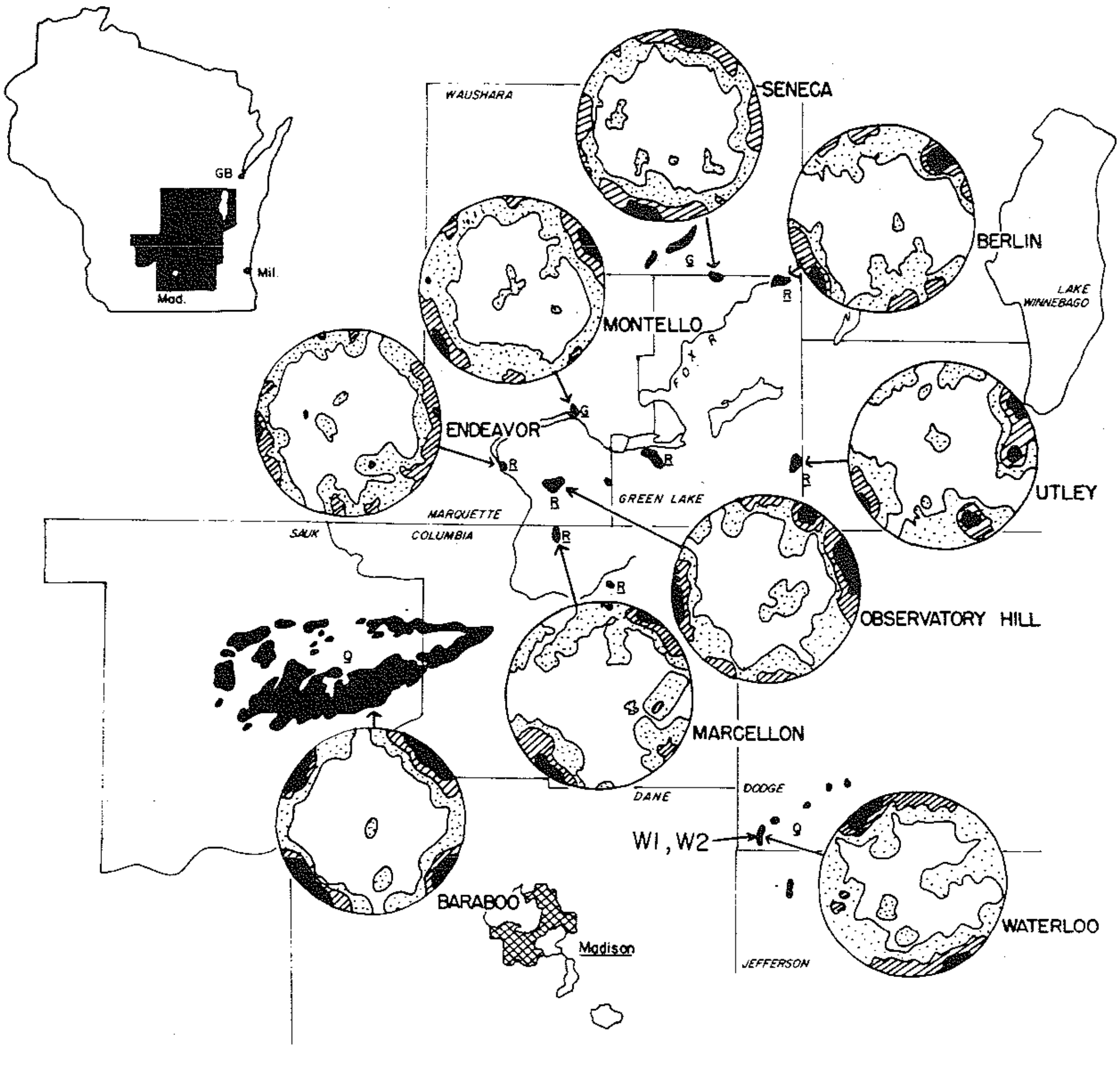

Figure 1. Locations of Precambrian rock outcrops in south-central Wisconsin with stereographic projections of joint data; 1, 5, 10% contours (rock types are: Q - quartzite, R - rhyolite, G - granite). Also shown is the location of the W1 and W2 core holes in the Waterloo quartzite.

We drilled and cored two boreholes in the Waterloo quartzite (280 m and 80 m deep). The cores of the two holes were mainly quartzite, occasionally cut by bands of schist, often less than 0.3 m in thickness but sometimes swelling to 3 m. Analysis of thin sections (Guidotti, 1977, Verbal communication) revealed that much of the schist contains porphyroblasts of dark red andalusite. At approximately 270 m depth in well W1 a 10 m thick band of fine grained, dense, dark intrusive was encountered which varied in color from black to dark red. Thin sections later revealed that this rock was a mafic sill which had been metamorphosed to a hornblende-oligoclase amphibolite (Haimson and others, 1978).

Rock Discontinuities

Surface Data

Joint orientations were sampled at nine Precambrian exposures in south-central Wisconsin. A summary of orientations and spacings is given in Table 1. Joints were measured along outcrop faces and quarry walls, and an effort was made to select exposures of varying orientations to assure coverage of all possible joint sets.

The locations of studied Precambrian exposures, together with stereographic projections of joint data are shown in Fig. 1. The dominant joint orientation in the Precambrian of south-central Wisconsin strikes northwest and dips nearly vertically. Dalziel and Dott (1970) note that this set in the Baraboo area is approximately normal to the axis of the Baraboo syncline and is coplanar with the paleotectonic greatest principal stress. It would seem likely, then, that the orientation of the Precambrian joints is related to the tectonic events responsible for the folding of the Baraboo syncline.

Another prominent joint orientation strikes northeast and dips subvertically (Waterloo, Baraboo, Montello, Utley). This joint set subparallels the regional direction of the largest horizontal compressive stress (N.60°E. $\pm$ 15°). Results of two sets of stress measurements in Wisconsin are given elsewhere in this paper.

Spacings in Table 1 are based on visual estimation. Joint spacing, however, would be expected to be greater at depth than at the surface owing to the large numbers of joints that appear near the surface due to weathering and stress relief on exposure. Coring is the best way to determine spacing and orientation of joints at depth.

Core Data

Montello Granite - During the month of June, 1975, a 215 m vertical corehole (3 in. diameter) was drilled at Montello, Wisconsin. As on the surface, two major groups of joints were encountered; rough, iron-oxide-coated joints, and smoother, often slickensided, chlorite-coated joints which are generally more abundant.

The core was continuous from 15 m of depth to the bottom of the hole. By reconstructing the core pieces, it was possible to run a continuous scribe along the core and determine the relative orientation of discontinuities and and other features in the core. Absolute orientation was then achieved by taking packer impressions of joints at 75, 135, and 185 m of depth, and

Table 1. Summary of Joint Data in Precambrian Rock Exposures
South-Central Wisconsin
(Dips are Vertical Unless Otherwise Stated)

Location	Rock Type	Orientations	Spacings (m)	Measurements
Montello	Granite	N.40°E.		276
		E. - W.	1 - 2	
		N.30°W.	1 - 4	
Seneca	Granite	N.55°E.		196
		N.69°W.		
		N. 4°E.	1 - 3	
Marcellon	Rhyolite	N.58°W.	1 - 2	106
		N.33°W.		
		N.40°E.		
		N.81°E. 75°SE		
Observatory Hill	Rhyolite	N.60°W.	1 - 2	100
		N.15°W.		
		E.- W.		
Utley	Rhyolite	N.33°W.	1 - 6	362
		N.2°W. 72°SW		
		N.64°E. 66°NW		
Berlin	Rhyolite	N.43°W.	1	129
		N.80°E.	1 - 2	
		N.52°E.		
		N.19°W.		
Endeavor	Rhyolite	N. 7°W.	0.2 - .8	106
		N.33°W.		
		N.86°W.		
		N.72°E.		
		N.22°E.		
Baraboo	Quartzite	N.45°W.	0.1 - 1	81
		N.35°E.		
Waterloo	Quartzite	N.60°E.		98
		N.75°W.		
		N.17°W. 65°SW		

orienting the impressions in the hole with a borehole surveying tool. Stereographic projections of the joint data (Fig. 2) show a predominance of horizontal fractures, as one would expect in a vertical borehole, as well as minor set striking N.30°W. and dipping 60° S.W.

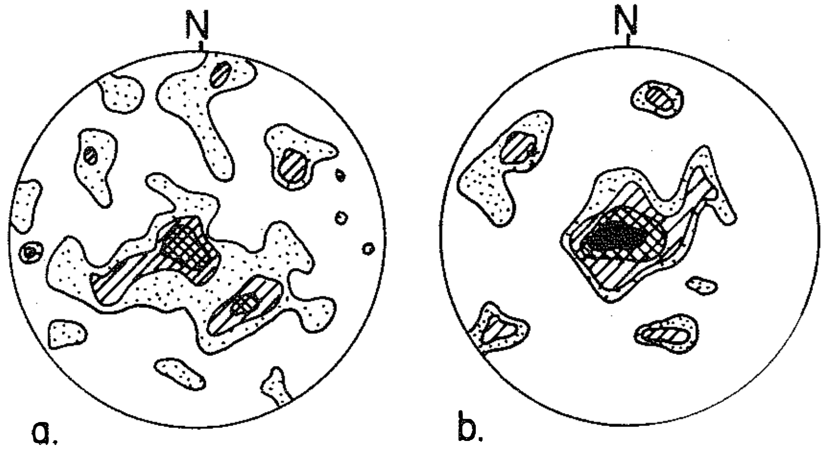

Figure 2. Equal-area plot of joints in the borehole at Montello: (a) chlorite coated joints; (b) iron-oxide coated joints. Contour intervals 2, 4, and 8 percent.

<u>Waterloo Quartzite</u> - During the summer of 1976 a 350 m long (280 m deep) 3 in. diameter corehold (W1) was drilled in the quartzite outcrop at a location some 3 km east of Waterloo, Wisconsin. The following summer an additional 80 m long NX corehole (W2) was drilled some 80 m west of W1. The absolute orientation of the core was determined by the method we had previously developed at Montello (see above).

The orientation of bedding planes in the Waterloo quartzite was found in both holes to be consistent with depth, striking at an average of N.50°W. and dipping 35° toward the northeast.

Figure 3 is an equal area plot showing the attitudes of the 1317 joints encountered in hole W1. The major joint set in W1 appears to strike in the range of N.70°W. to N.30°W. and dip at approximately 45° to the southwest. This correlates with the two secondary sets at the surface (Fig. 3), at least with respect to joint strike. The third set visible on surface, striking at N.60°E., is not observed in the hole because the inclination direction of the hole is N.30°E. set. Thus the number of N.60°E. joints intersected was insignificant.

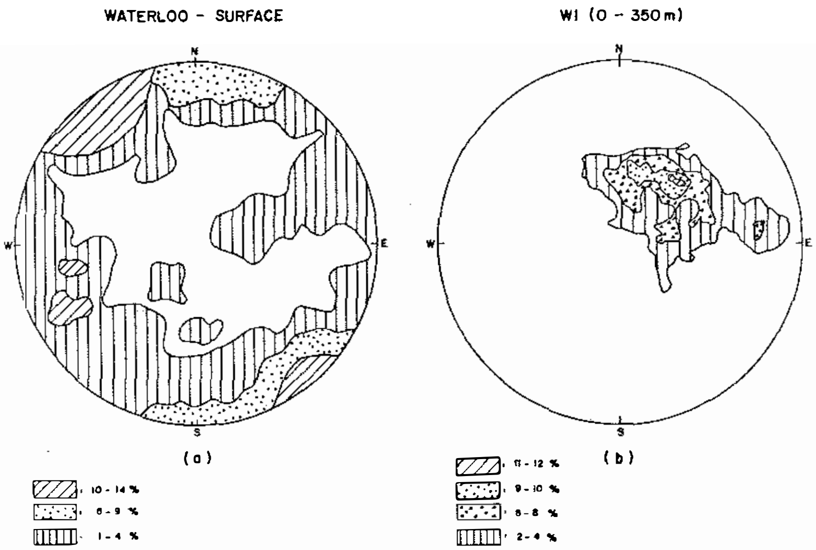

Figure 3. Equal-area plots of joints near Waterloo: (a) on surface; (b) in hole W1

Figure 4 is a stereographic projection of all the joints in hole W2, and for comparison Figure 4 is a similar plot for all the joints in the top of 115 m of hole W1. The two plots compare quite well, with most of the joints subhorizontal. The dominant set in both is one striking at N.30°W. to N.60°W. and dipping 20° to the northeast.

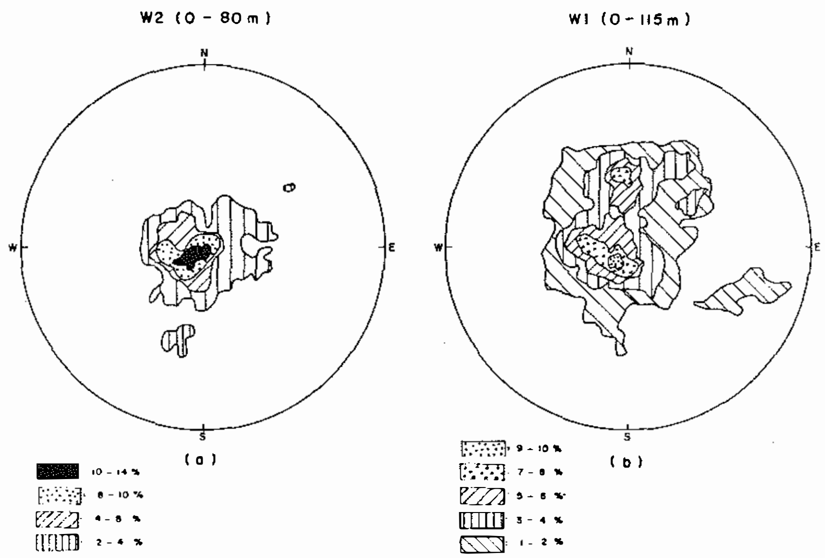

Figure 4. Equal-area plots of joints near Waterloo: (a) in hole W2; (b) in the top 115 m of hole W1.

In logging the two cores we recorded information related to joint roughness, coating and filling, degree of openness, presence of slickensides, and other joint characteristics. Table 2 details the major types of joints encountered and their spacings in the two holes. The clay filled joints are usually the most troublesome in engineering applications but in the Waterloo quartzite they appear to be rather rare. The micaceous joints have very smooth and planar surfaces that feel slippery to the touch. The talc coat is very light and does not appear to affect the mechanical properties of the joints.

Table 2

Joint Types and Spacings
in holes W1 and W2

Joint Type	Spacing (m)
Rough, clean	0.25 - 0.7
Smooth, clean	.3 - 1
Talc coated	.7 - 2
Mica coated	1 - 3
Clay filled (W2 only)	20

STATE OF STRESS

Montello Granite

We used our drillhole at Montello in order to conduct six hydrofracturing stress measurements between the depths of 75 m and 188 m. A detailed description of this method of stress determination is given by Haimson (1974, 1977). Five of the borehole packer impressions after hydrofracturing yielded both vertical and nearly horizontal fracture traces, indicating that the least principal stress acted in the vertical direction. All five vertical fractures were within $\pm$ 20° from the mean direction of N.63°E. In these five tests, two shut-in pressures were identified, the first corresponding to the vertical fracture and, hence, yielding the least horizontal compressive stress (σ_{Hmin}), and the second approximately equal to the overburden weight (σ_V). The latter was determined in the laboratory at 0.026 MPa*/m x depth (m). °Hmin appeared insensitive to the minor depth variations of these tests and was limited between 6.2-8.2 MPa. The maximum horizontal compressive stress (σ_{Hmax}) calculated from the recorded breakdown pressure, the first shut-in pressure and the laboratory determined hydrofracturing tensile strength (= 17 MPa), varied between 14 - 20 MPa (Fig. 5). For example, at 135 m depth the principal stresses are: σ_V = 3.5 MPa, σ_{Hmin} = 7 MPa at N.27°W., σ_{Hmax} = 16 MPa at N.63°E. It should be noted that the horizontal stresses are considerably higher than the vertical component; this appears to be common to shallow measurements in ancient shields. The direction of the principal stresses, although consistent with the general trend in the continental U.S., does not reflect late Precambrian deformation activities in southern Wisconsin (Haimson, 1977).

*MPa (megapascal) is a metric unit of pressure, equivalent to 10 bars, or 145 psi (pounds per square inch).

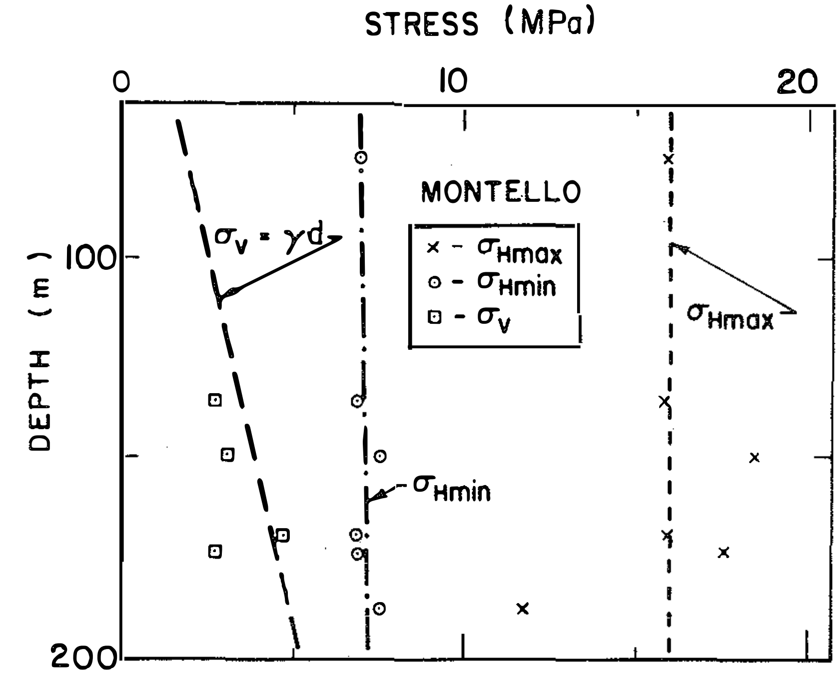

Figure 5. Variation of the three principal stresses with depth (75-200 m) in the Montello granite.

Waterloo Quartzite

We conducted three hydrofracturing stress measurements in hole W1 and ten in hole W2. The reason for the fewer tests in the deeper hole was that we encountered mechanical problems due to unusually frigid weather during the month set aside for testing (November 1976).

Testing procedure in hole W1 was as described in previous publications (Haimson, 1974, 1977), and consisted of two down-hole trips for each test, one to induce hydrofracturing using a straddle packer, and the other to determine hydrofracture inclination and direction using an impression packer. In hole W2 a newly designed straddle packer which does not require retrieval after every test was used successfully. This improvement saved some 30% of the total time required to complete our measurements. It can save close to 50% of the time in deeper tests (500 m or more).

Based on the recorded breakdown and shut-in pressures and the fracture impressions, the following state of stress was determined at Waterloo. Immediately below the surface, within 20 m depth, two tests in W2 and one in W1 show that the largest horizontal compressive stress is oriented in a north to northwest direction. On the other hand, in the range of depths tested beneath that shallow zone all the hydrofractures in both holes indicate that °Hmax is oriented at N.60°E. ± 15° (Figure 6). With respect to

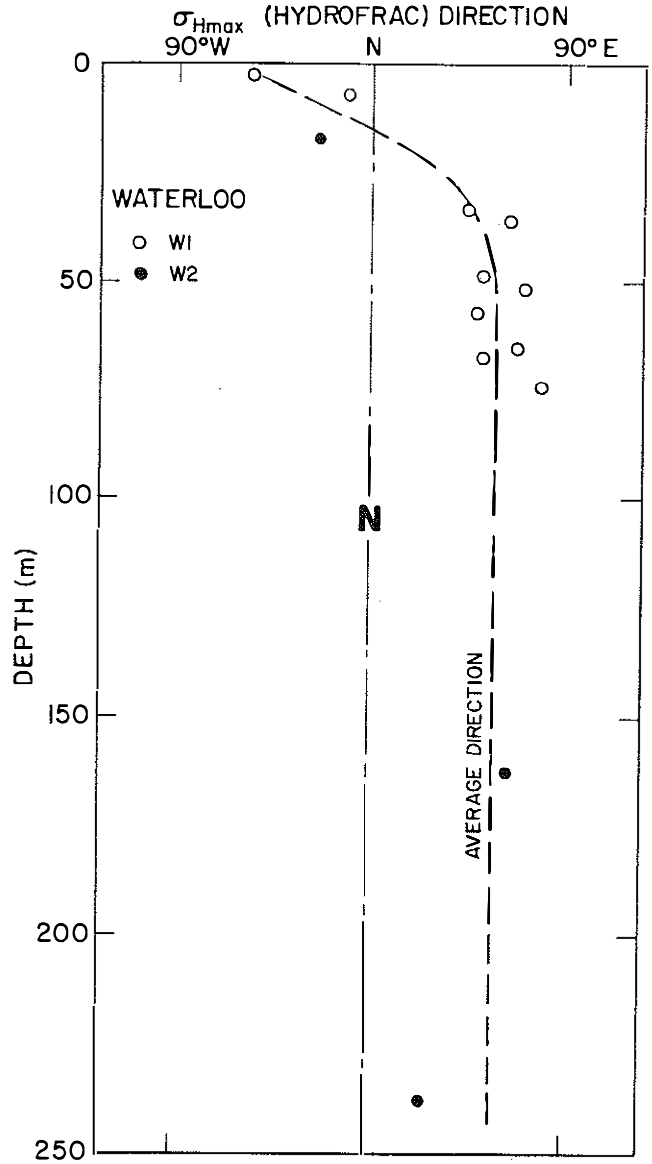

Figure 6. Variation of maximum horizontal stress direction with depth (0 - 250 m) in the Waterloo quartzite.

magnitudes, in the top 20 m the least horizontal compressive stress is in the range 1.0-1.5 MPa, and the largest horizontal stress between 1.5-2.5 MPa. In the 50-240 m range a separate but consistent stress field appears to prevail with $\sigma_{Hmin} = 5.5 + 0.008$ d and $\sigma_{Hmax} = 9.5$ to 0.012 d (by linear regression), where stresses are in MPa and d is depth in meters (Fig. 7). The vertical stress (σ_V) is given, based on rock density, by $\sigma_V = 0.026$ d. For example, at a depth of 200 m the principal stresses are: $\sigma_V = 5.2$ MPa, $\sigma_{Hmin} = 7.1$ MPa at N.30°W. and $\sigma_{Hmax} = 11.9$ MPa at N.60°E. Significantly, at all tested depths the horizontal principal stresses are higher than the vertical. This stress regime is very similar to that at Montello, some 80 km northwest of Waterloo, indicating a possible regional stress consistency.

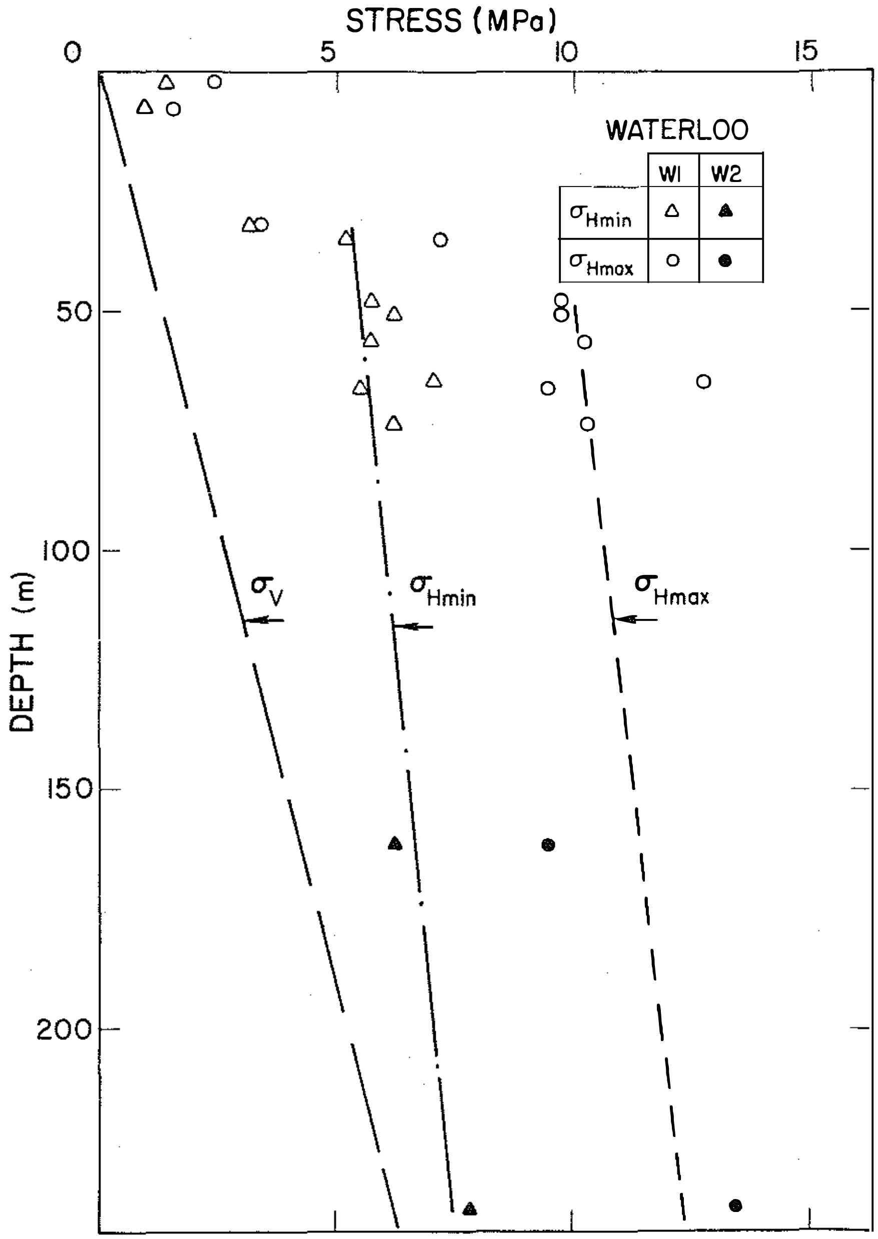

Figure 7. Variation of the three principal stresses with depth (0.250 m) in the Waterloo quartzite.

MECHANICAL PROPERTIES

Surface vs. Core

We carried out extensive laboratory mechanical testing in four Precambrian rocks, namely Montello granite, Waterloo Quartzite, Baraboo quartzite, and Berlin Rhyolite. Large blocks of these rocks were collected in quarries and brought to our laboratory where specimens were cored out and prepared for testing. Twenty-four specimens of size 5.5 cm diameter x 14 cm long, were prepared for each rock. Twelve were tested in uniaxial compression and twelve were tested in uniaxial tension.

In addition, we used the core obtained at Montello and Waterloo for further testing of mechanical properties at depth. The core was 5 cm in diameter and was tested only in the direction of its axis. Three to five specimens per depth of core were prepared (60, 120 and 180 m in the Montello granite; 8, 27, 46, 77, 85, 107, 125, 240 and 270 m in W1 core and 9, 25, 39, 45, 60 and 73 m in W2 core - both of Waterloo quartzite).

Prior to mechanical testing the density (γ) of each specimen was determined by measuring mass and volume, and the dynamic properties were established by placing each rock cylinder in an "acoustic bench" where the two seismic velocities (V_p, V_s) were recorded. Two pairs of electric resistance strain gages were then epoxied to each specimen, two in the axial direction and two in the lateral plane. Each specimen was then placed in a loading machine where either axial compression or axial tension was applied. With the help of the strain gages continuous recordings of axial load vs. axial strain and axial load vs. lateral strain were produced. These were used to calculate the failure strength (either in compression, C_o, or in tension, T_o) and the two elastic properties: Young's modulus, or modulus of deformation (E for compression, E_T for tension), and Poisson's ratio (ν, ν_T). The Young's modulus is a measure of the stiffness of the rock (the ratio between the axial load and the correspondant axial strain). The Poisson's ratio is the negative ratio between the lateral strain and the axial strain.

Table 3 gives the average value obtained for each of the parameters in the different rocks. Also shown are the dynamic elastic moduli (E_D, ν_D) which were obtained from the measured values of γ, V_p and V_s, using well known formula.

With respect to strength, the four Precambrian rocks tested are very strong in both tensional and compressional stress fields. According to one classification (Deere, 1968) any rock having a uniaxial compressive strength (C_o) higher than 220 MPa can be considered as "very strong". Table3 shows that the four rocks tested are in the range of 200-400 MPa. Only the dike material in the Montello granite core is considerably weaker. Surprisingly, both the granite and the quartzite cores exhibit lower compressive strengths (10% and 20% respectively) than the surface rock. The tensile strength values, although only about 5% of C_o, are considered very high if we recall that the accepted value for very strong rocks in tension is 10 MPa.

The compressional modulus of deformation (E) results indicate very high stiffness for all four rocks and the dike, exceeding that of aluminum (6.9 x 10^4 MPa). No significant differences are observed between core and surface rock. In tension, as expected (Haimson and Tharp, 1974), the Young's modulus

Table 3

Mechanical Properties of Four Precambrian Rocks in South-Central Wisconsin

Rocks	γ gm/cc	C_o MPa	T_o MPa	V_p m/sec	V_s m/sec	E $\times 10^4$ MPa	E_T $\times 10^4$ MPa	E_D $\times 10^4$ MPa	ν	ν_T	ν_D
Montello Granite surface	2.64	330	15	5,270	3,180	7.5	5.0	6.5	0.21	0.13	0.21
Montello Granite core	2.64	300		4,650	3,040	7.5		5.4	0.25		0.13
Montello Dike, core		150		4,600	3,260	7.5		5.3	0.28		0
Waterloo Quartzite, surface	2.67	241		5,200	3,300	8.0		7.0	0.11		0.12
Waterloo Quartzite, core	2.67	205	10	5,300	3,530	7.2	4.9	7.2	0.15	0.06	0.10
Baraboo Quartzite, surface	2.67	340	19	5,680	3,640	8.0	7.9	8.1	0.12	0.10	0.15
Berlin Rhyolite surface	2.66	410	14	4,795	3,055	7.5	4.2	5.7	0.23	0.13	0.14

(E_T) is lower because of microcrack opening in the pulling process of the test. An average ratio of E/E_T = 3/2 appears to prevail. The range in Poisson's ratio (and T) for all four rocks and the dike is 0.1 to 0.3. The core exhibits higher than the surface rock, the tensile Poisson's ratio (T) is consistently lower than the compressive counterpart.

The dynamic values E_D and D were inserted in Table 3 for comparison. Exact correlation between these values and those obtained statically (E, E_T and ν, ν_T) has not been established yet because loading conditions are different. However, the closeness between static and dynamic parameters attests to both the high quality of the rocks and to the reliability of the test results. Again the core and the surface rocks yield very similar results which may lead to the conclusion that the surface rock has undergone very little weathering and its elastic properties are representative of the rock at depth.

Waterloo Quartzite Anisotropy

A series of tests was designed to evaluate the degree of anisotropy in the Waterloo quartzite. It was felt that the almost invisible quartzite bedding could be a serious source of anisotropy in the otherwise massive rock. Cylindrical specimens were cored at 15° intervals between the plane of bedding and the direction 90° to it as shown in Figure 8. Specimens 5.5 cm in diameter and 12.5 cm long were prepared out of the surface block. The subsurface specimens were drilled out of the 5 cm diameter core and were limited to 2 cm x 5 cm size. Thus, only the uniaxial compressive strength (C_o) was determined for them. Depths tested were 8 m, 114 m, 140 m, 240 m and 270 m (W1 core), and 46 m and 73 m (W2 core). The results are summarized in Figure 8. The anistropy in C_o is quite substantial with a minimum strength of 165 MPa at 60° (the angle is as defined in Figure 8 by θ), some 40% lower than the maximum value of 272 MPa at 15°. Nevertheless, the quartzite can be classified as a very strong rock overall.

The elastic parameters Young's Modulus and Poisson's ratio were determined for each 15° angle only on surface samples. The values were verified through testing of core specimens from different depths. Figure 8 shows that E varies only by some 12% between the maximum of 8.5 x 10^4 MPa (at 30°) and the minimum of 7.5 x 10^4 MPa (at 75°). Note the high degree of stiffness in this rock. The values of are practically independent of the angle and yield a consistent value of 0.1. Hence, based on uniaxial compressive tests there appears to be considerable anisotropy with respect to strength (C_o) but only minor anistropy with respect to elastic parameters.

A series of disc (Brazilian) tests in core specimens taken from hole W2 (depths of 3 m, 10 m, 40 m, 60 m and 70 m) was aimed at determining the extent of anistropy with respect to the tensile strength (T). Specimens were loaded at 30° increments with respect to North, remembering that in a vertical core the loading in Brazilian testing is horizontal. The results are shown in Figure 9, the eastwest loading direction yielding the weakest T value at 12 MPa, 17% lower than the 14.5 MPa in the north-south direction. As far as engineering applications are concerned this low anisotropy can be considered generally insigificant. The average value of T attests to a very strong rock in tension. The average ratio Co/T is 17:1.

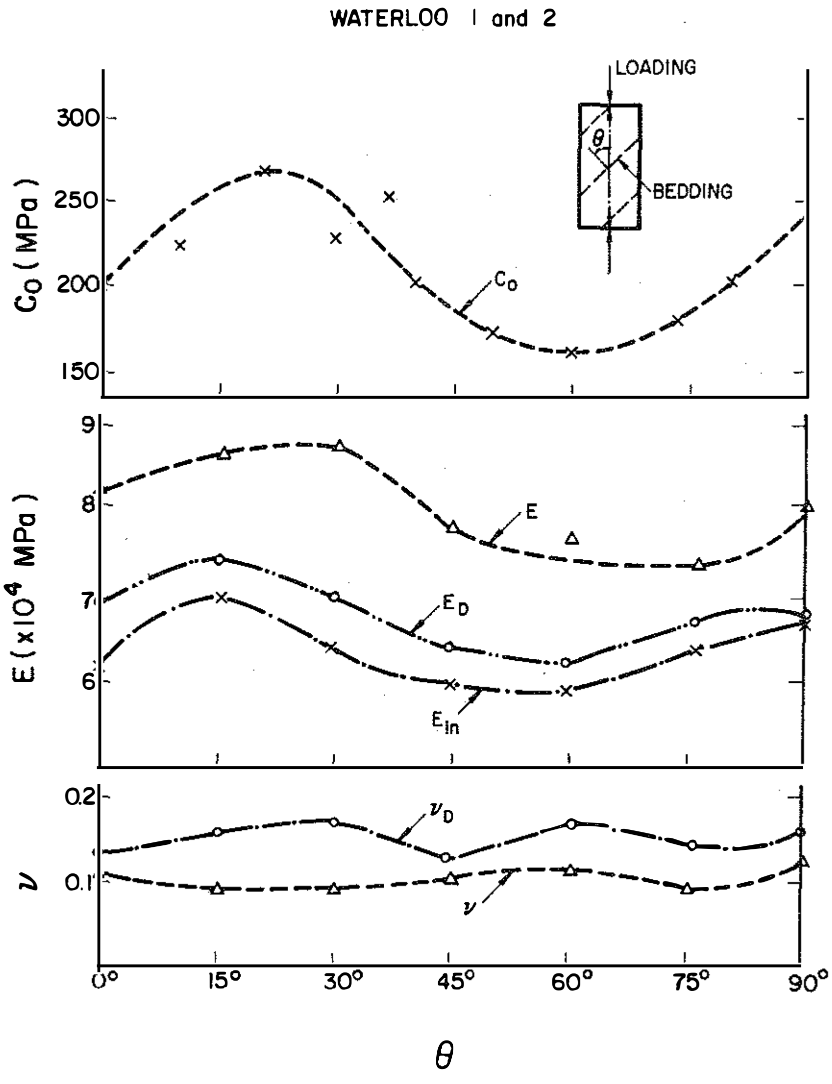

Figure 8. Variation of the uniaxial compressive strength (C_o), the average Young's modulus (E) and the Poisson's ratio ( ) with the angle - Waterloo quartzite (E_D and D are the dynamic values obtained from the measured compressional and shear velocities, Ein is the initial Young's modulus at the onset of loading).

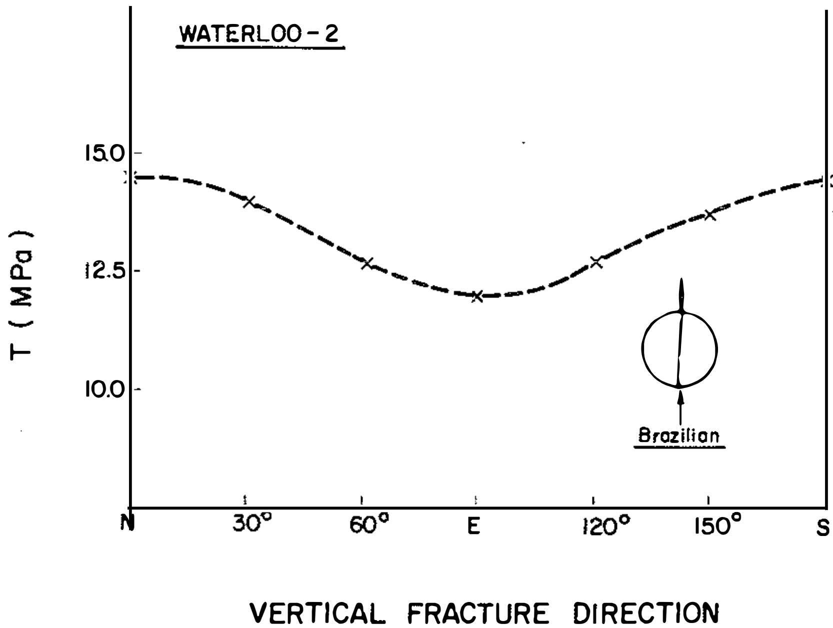

Figure 9. Variation of the Brazilian test tensile strength (T) with the direction of loading in samples of vertical core from hole W2 - Waterloo quartzite.

Most of the tested specimens were first placed in an acoustic bench where the travel times of both compressional and shear waves were measured. The compressional wave velocity varied from a low Vp = 5010 m/sec at θ= 45° (θ is defined in Figure 8) to a high 5385 m/sec at 15°. The shear wave velocity range extended from Vs = 3150 m/sec at 60° to 3400 m/sec at 0°. From the two velocities we calculated the dynamic elastic parameters of the Waterloo quartzite, E_D and ν_D, shown in Figure 8.. The dynamic Young's modulus varied with respect to angle θ in a manner similar both to E and to the initial value of the tangental Young's Modulus at the onset of the uniaxial loading (E_{in}). The low E_D at = 60° (6.3 x 10^4 MPa) was 11% less than the high E_D at 15° (7.1 x 10^4 MPa), yielding an amount of anistropy very similar to E. However, the average value of E_D is about 15% lower than E. The dynamic Poisson's ratio averaging 0.15 was higher than the static ν , but similar to the behavior of ν , it did not appear to be affected by rock anistropy (Figure 8).

Rock Mass

Montello Granite

Compressional and shear velocities were measured in the borehole by lowering a seismic cap to the depths of 60, 120 and 180 m and recording the arrivals at the surface. A compressional velocity of 5100 m/sec and a shear velocity of 3355 m/sec were computed. They both compare rather well with the laboratory results in intact specimens attesting to the high quality of the granite mass.

Waterloo Quartzite

We have so far conducted a surface seismic refraction survey in an attempt to determine the rock mass compressional and shear velocities of the Waterloo quartzite. A compressional velocity of 3850 m/sec and a shear velocity of 2120 m/sec were determined. The two values were used to evaluate the near surface dynamic Young's modulus (3.3 x 10^4 MPa) and Poisson's ratio (0.28). Both seismic velocities are considerably lower than those obtained in intact rock specimens taken from the core. As a result the field dynamic Young's modulus is less than half of the laboratory measured value. This should indicate a rather discontinuous rock mass. However, we feel that the low velocity values are due to an abundance of open joints near the surface. We are planning a series of velocity measurements between the two boreholes which should yield more realistic values of the rock mass characteristics of depth.

ACKNOWLEDGMENTS

This project has been supported by the National Science Foundation, the Energy Research and Development Administration, the Wisconsin Utilities Research Foundation, and the Wisconsin Alumni Research Foundation. Graduate students T. Doe, S. Erbstoesser, M. Ma, M. O'Donnell and N. Ren carried out much of the reported work.

REFERENCES CITED

Aldrich, L. T., G. W. Witherill, M. N. Bass, W. Compston, G. L. David, and G. R. Tilton, 1959, Mineral age measurements: Carnegie Instit Washington, Yearbook 58, p. 246-247.

Asquith, G. B., 1964, Origin of the Precambrian Wisconsin Rhyolites: Jour. Geol., vol. 68, p. 835-847.

Dalziel, I. W. D., and Dott, R. H., 1970, Geology of the Baraboo District, Wisconsin: Wisconsin Geol. and Nat. History Survey Inf. Cir. 14, 164 p.

Deere, D. U., 1968, Geological Consideration: in Rock Mechanics in Engineering Practice, ed. by K. G. Stagg, and O. C. Zienkiewicz, Wiley, London, p. 1-19.

Haimson, B. C., 1974, A Simple method for estimating in situ stresses at great depths: in Field Testing and Instrumentation of Rock: Amer. Soc. for Testing and Materials Spec. Tech. Publ. 554, p. 156-182.

Haimson, B. C., 1977, Crustal stress in the continental United States as derived from hydrofracturing tests: in The Earth's Crust (Amer. Geophs. Union Monograph 20), J. Heacock, Ed., p. 576-592.

Haimson, B. C., T. W. Doe, S. R. Erbstoesser and G. F. Fuh, 1976, Site characterization for tunnels housing energy storage magnets: in Site Characterization (Proc. 17th U. S. Symposium on Rock Mechanics), Utah Engr. Exper. Station, Salt Lake City, p. 4B4:1-9.

Haimson, B. C., Ma, M. S., O'Donnell, M., and Ren, N. K., 1978, Site investigation for energy storage caverns at Waterloo, Wisconsin: in Proc. Third Int'l Congress of the Int'l Assoc. of Engr. Geology, Madrid (in press).

Haimson, B. C. and T. M. Tharp, 1974, Stresses around boreholes in bilinear elastic rock: Soc. of Petrol. Engr. Journal, vol. 14, p. 145-151.

Smith, E. I., 1978, Precambrian rhyolites and granites in south central Wisconsin: field relations and geochemistry: Geol. Soc. America Bull., vol. 89 (in press).

Stark, J. T., 1930, Precambrian water laid tuff in the Baraboo, Wisconsin District: Jour. Geol., vol. 57, p. 466-471.

Van Schumus, W. R., Thurman, E. M., and Peterman, Z. E., 1975, Rb-Sr data for older Precambrian rocks in eastern and central Wisconsin: Geol. Soc. America Bull., vol. 86, p. 1255-1265.

Wisconsin Superconducting Energy Storage Project, 1974, Feasibility study report, vol. 1, Engineering Experiment Station, University of Wisconsin-Madison.

Wisconsin Superconducting Energy Storage Project, 1976, Feasibility study report, vol. II, Engineering Experiment Station, University of Wisconsin-Madison.