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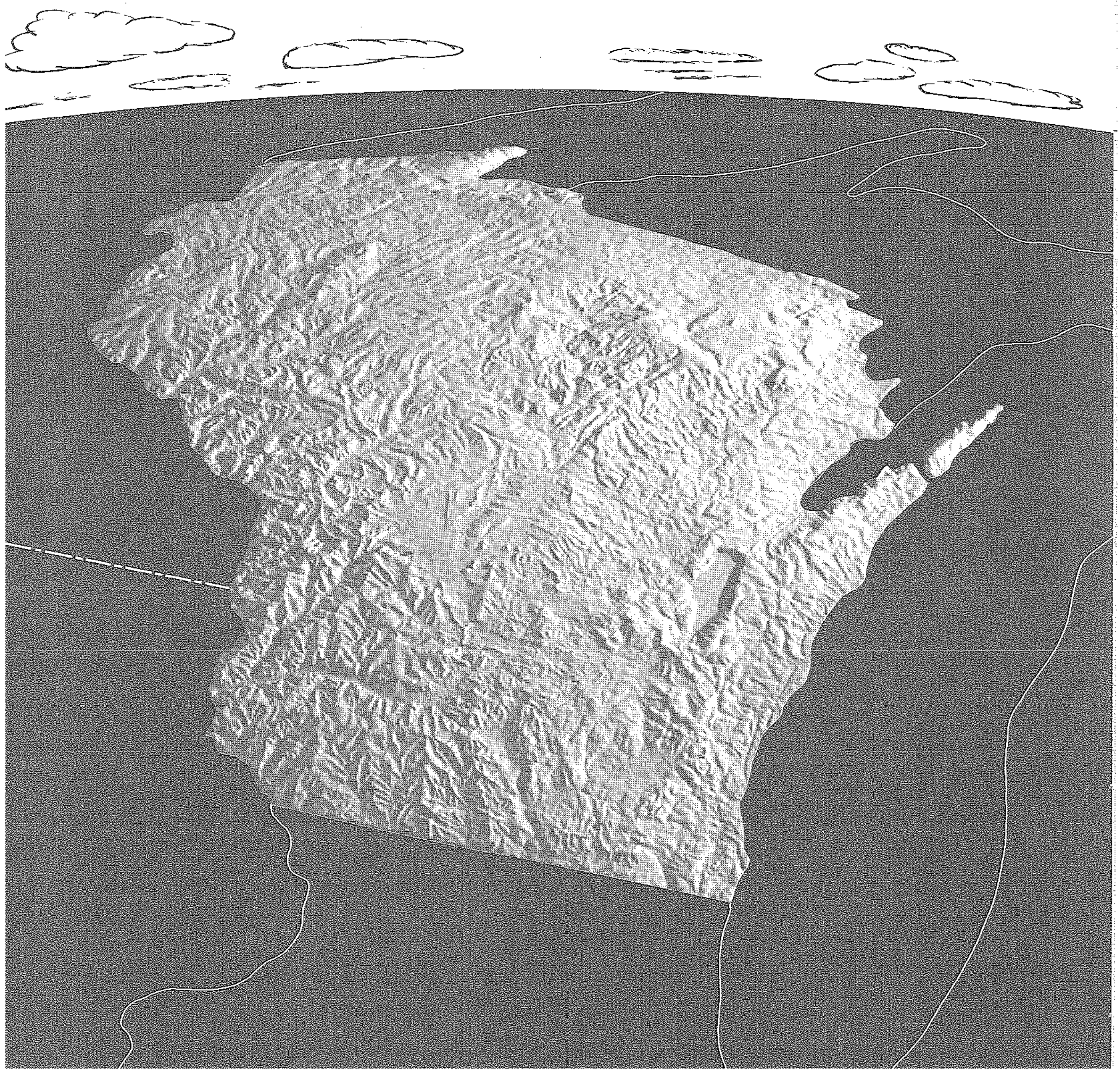

Cover: An oblique photograph of a plastic raised relief map of Wisconsin by Hans J. Stolle a graduate student in the Geography Department, University of Wisconsin - Madison.

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Introduction to Precambrian Rocks of South-Central Wisconsin

by

Eugene I. Smith

Geochronology of the Southern Wisconsin Rhyolites and Granites

by

W.R. Van Schmus

Engineering Geology, Stress Regime and Mechanical Properties of some Precambrian Rocks in South-Central Wisconsin

by

B.C. Haimson

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PREFACE

"Geoscience Wisconsin" is a serial that addresses itself to the geology of Wisconsin -- geology in the broadest sense to include rocks and rocks as related to soils, water, climate, environment, and so forth. It is intended to present timely information from knowledgeable sources and make it accessible with minimal time in review and production to the benefit of private citizens, government, scientists, and industry.

Manuscripts are invited from scientists in academic, government, and industrial fields. Once a manuscript has been reviewed and accepted, the authors will submit a revised, camera-ready copy of the paper, and the Geological and Natural History Survey will publish the paper as funds permit, distribute copies at a nominal cost, and maintain the publication as a part of the Survey list of publications. This will help to insure that results of research are not lost in the archival systems of large libraries, or lost in the musty drawers of an open-file.

Over 40 years ago, in 1935 the Kansas Geological Society organized a geological excursion that included the Precambrian inliers in southeastern Wisconsin. In the last five years, Eugene I. Smith, W. R. Van Schmus, and B. C. Haimson have undertaken petrologic, geochronologic, and engineering studies of the granites, rhyolite and quartzites in that area. This issue of "Geoscience Wisconsin" presents brief summary reports on those studies. A companion volume is Wisconsin Geological and Natural History Survey Geological Field Guide Book Number 2 which was prepared for the 24th Annual Institute on Lake Superior Geology that was hosted by the University of Wisconsin-Milwaukee from 9-14 May 1978.

We encourage submission of manuscripts relating to Wisconsin geology. Special consideration will be given papers which deal with timely topics, present new ideas, and have regional or statewide implications.

Wisconsin Geological and Natural
History Survey

INTRODUCTION TO PRECAMBRIAN ROCKS OF SOUTH-CENTRAL WISCONSIN

by

Eugene I. Smith[1]

THE INLIERS

Introduction and Geologic Setting

Exposures of Precambrian rocks in south-central Wisconsin are for the most part granites, quartzites and rhyolites (Smith, 1978a). Basalts, andesites, and dacites are subordinate rock types and occur as thin dikes. Each exposure (inlier) is surrounded and partially covered by Cambrian sandstone and Pleistocene drift and outwash. Except for the Waterloo Quartzite that crops out in the Crawfish River Valley, most of the Precambrian inliers are located in the Fox River Valley (Figure 1), (Table 1). To the west of the Fox River Valley, in the Baraboo Range, Precambrian quartzite stratigraphically overlies a terrain composed of acidic igneous rock and isolated intrusions of gabbro (Stark, 1932; Gates, 1942; Dalziel and Dott, 1970).

The Fox River Valley exposures are composed of two varieties of rhyolite, and granite. Porphyritic rhyolites are found in the Berlin, Utley, Endeavor, Observatory Hill and Taylor Farm inliers and contain large (1 to 5 mm) pink to white feldspar, and quartz phenocrysts set in a black, dark gray or reddish brown matrix. Texturally variable rhyolites occur in the Marquette, Marcellon and Baraboo exposures, and are characterized by the change from phenocryst-rich, quartz-bearing rhyolites to phenocryst-poor rhyolites with a paucity of quartz and abundant plagioclase. These rocks are black to dark gray in color and vary considerably in texture. The rock may be banded, brecciated, spherulitic or massive. Both varieties of rhyolite are interpreted as ash-flow tuffs. Pink to red fine- to medium-grained granites are exposed at Montello and in the Redgranite area. Quartz and alkali feldspar comprise 90 to 98% of the rock; perthitic, granophyric and myrmeketic textures are common. More information on the petrology of these and other rock types of Precambrian age in south-central Wisconsin is presented in Smith (1978a) and in the guidebook to these rocks that follows.

U-Pb dating of zircons in the Fox River Valley rhyolites and granites (Van Schmus, 1976; 1978) indicates an average age of 1765 $\pm$ 10 m.y. B. P. for these rocks. Rocks of this age are not restricted to the Fox River Valley and occur throughout the state (Figure 2). Rhyolites and granites in the Baraboo area are most likely of the same age as the Fox River Valley rocks. The dates of the Fox River Valley rocks are distinctly younger than those obtained for volcanic rocks in the Wausau area (1850 $\pm$ 30 m.y. B.P.; Van Schmus, 1976), and for volcanic rocks in northeastern Wisconsin (1850-1900 m.y.; Banks and Cain, 1969). On the other hand, the inliers are significantly older than the Wolf River Batholith in north-eastern Wisconsin that is dated at 1500 m.y. old (Van Schmus and others, 1975a).

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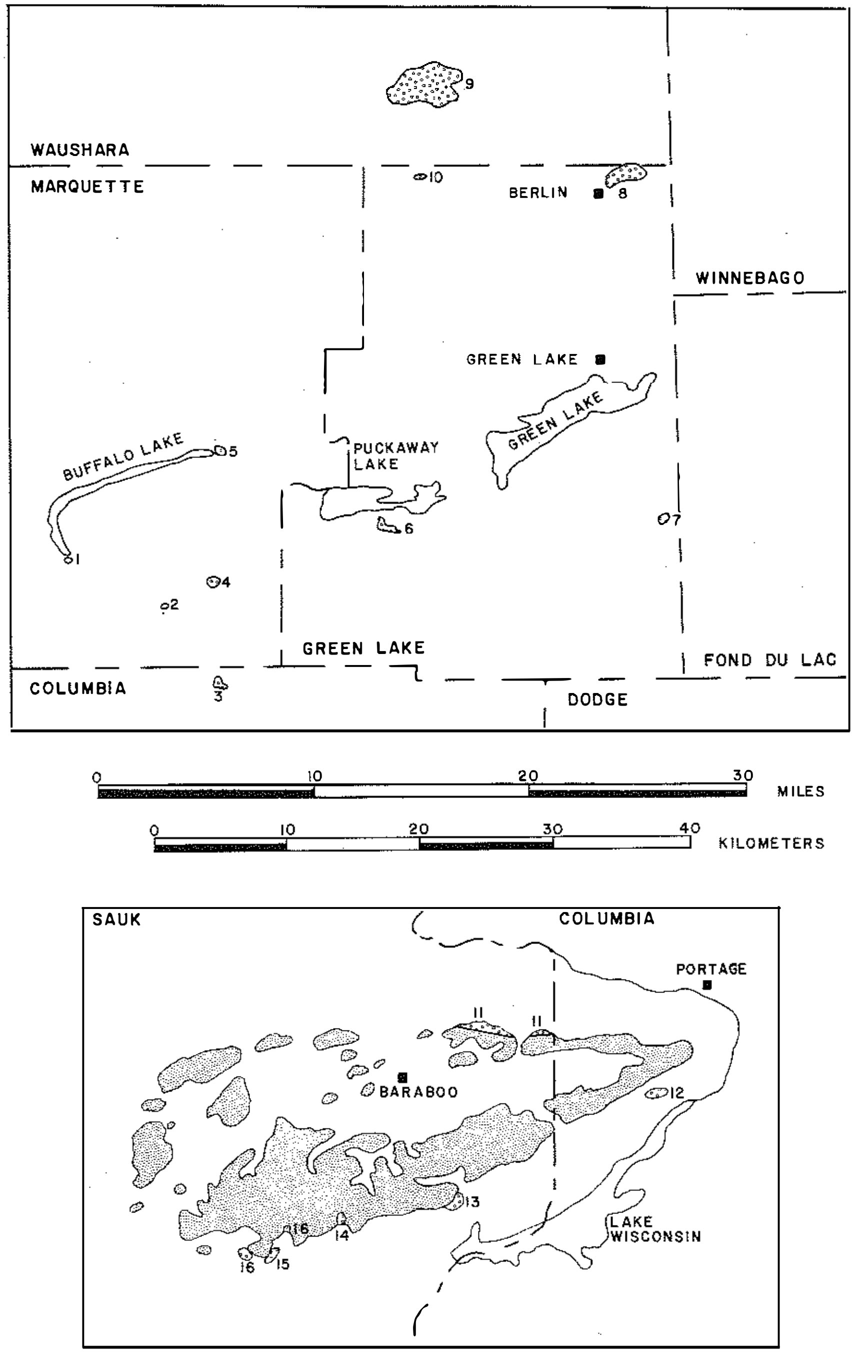

Figure 1. Index map of rhyolite and granite inliers and associated Precambrian exposures in the Fox River Valley (upper map) and the Baraboo area (lower map). (1) Endeavor rhyolite. (2) Taylor Farm rhyolite. (3) Marcellon rhyolite. (4) Observatory Hill rhyolite. (5) Montello granite. (6) Marquette rhyolite. (7) Utley rhyolite. (8) Berlin rhyolite. (9) Granite at Redgranite. (10) Granite at Pine Bluff. (11) Lower Narrows rhyolite. (12) Caledonia Church rhyolite. (13) South Limb rhyolite. (14) Naxter Hollow granite. (15) Denzer rhyolite. (16) Denzer diorite. Dotted pattern on lower map is the Baraboo Quartzite. (From Smith, 1978a).

Table 1

SUMMARY OF THE GEOLOGY OF THE FOX RIVER VALLEY RHYOLITES AND GRANITES, AND THE IGNEOUS ROCKS IN THE BARABOO AREA

Exposure	Location	Important Rock Types	Comments	References
Montello	sec. 9, T15N, R10E.	Granophyric granite, metabasalt.	Rock contains less than 2% chlorite and opaque minerals.	(Buckley, 1897)
Red Granite	sec. 1, T17N, R11E; NW¼, T18N, R12E;NE¼, T18N, R11E.	Granophyric granite, metabasalt, porphyritic granite.	Rock contains less than 5% chlorite and opaque minerals.	(Buckley, 1897) (Weidman, 1904)
Berlin	SE¼, sec. 3, T17N, R13E.	Porphyritic rhyolite	Rhyolite is locally sheared.	(Buckley, 1897)
Marquette	sec. 34-35, T15N,R11E; sec. 1-2, T14N, R11E.	Porphyritic and fine-grained rhyolite, breccia, andesite dike.	Rhyolite is folded and faulted.	(Smith,this paper)
Observatory Hill	SW¼, sec. 8, T14N, R10E.	Porphyritic rhyolite, dikes of coarse-grained rhyolite and metabasalt	Little or no textural variation.	(Hobbs and Leith, 1907)
Taylor Farm	NE¼, sec. 13, T14N, R9E.	Porphyritic rhyolite	Location incorrect in many earlier references.	(Hobbs and Leith, 1907)
Endeavor	S½, sec. 5, N½ sec. 8, T14N, R9E.	Porphyritic rhyolite	Little or no textural variation	(Hobbs and Leith, 1907)
Marcellon	sec. 7, T13N, R10E.	Texturally variable rhyolite, metabasalt	Folded into a northeast trending antiform	(Smith, this paper)
Utley	N½, sec. 36, T15N, R13E.	Porphyritic rhyolite, felsic and metabasalt dikes.	Zones of spherulites and lithophysae trend N50W.	(Gram, 1947)
Baraboo	sec. 21,22,23, T12N, R7E.	Texturally variable rhyolite.	Lies below Baraboo Quartzite.	(Dalziel and Dott, 1970)
Caledonia Church	NE¼,sec. 3, T11N, R8E.	Fine-grained rhyolite and breccia.	Lies below Baraboo Quartzite.	(Dalziel and Dott, 1970)
Baxter Hollow Granite	SW¼, sec. 33, T11N, R6E	Fine-grained granite	Intrusive into rhyolite, relationship to Baraboo Quartzite unclear.	(Gates, 1942)
Denzer Rhyolite	SE¼, sec. 11, T10N, R5E.	Fine-grained bedded rhyolite.	Volcanoclastic sand-stone ?	(Stark, 1932)
Denzer Diorite	sec. 9 and 10, T10N, R5E.	Coarse-grained diorite	Contacts with adjacent units not exposed.	(Stark, 1932)

Other rhyolite inliers shown on Dutton and Bradley (1970) could not be located in the field. They probably do not exist.

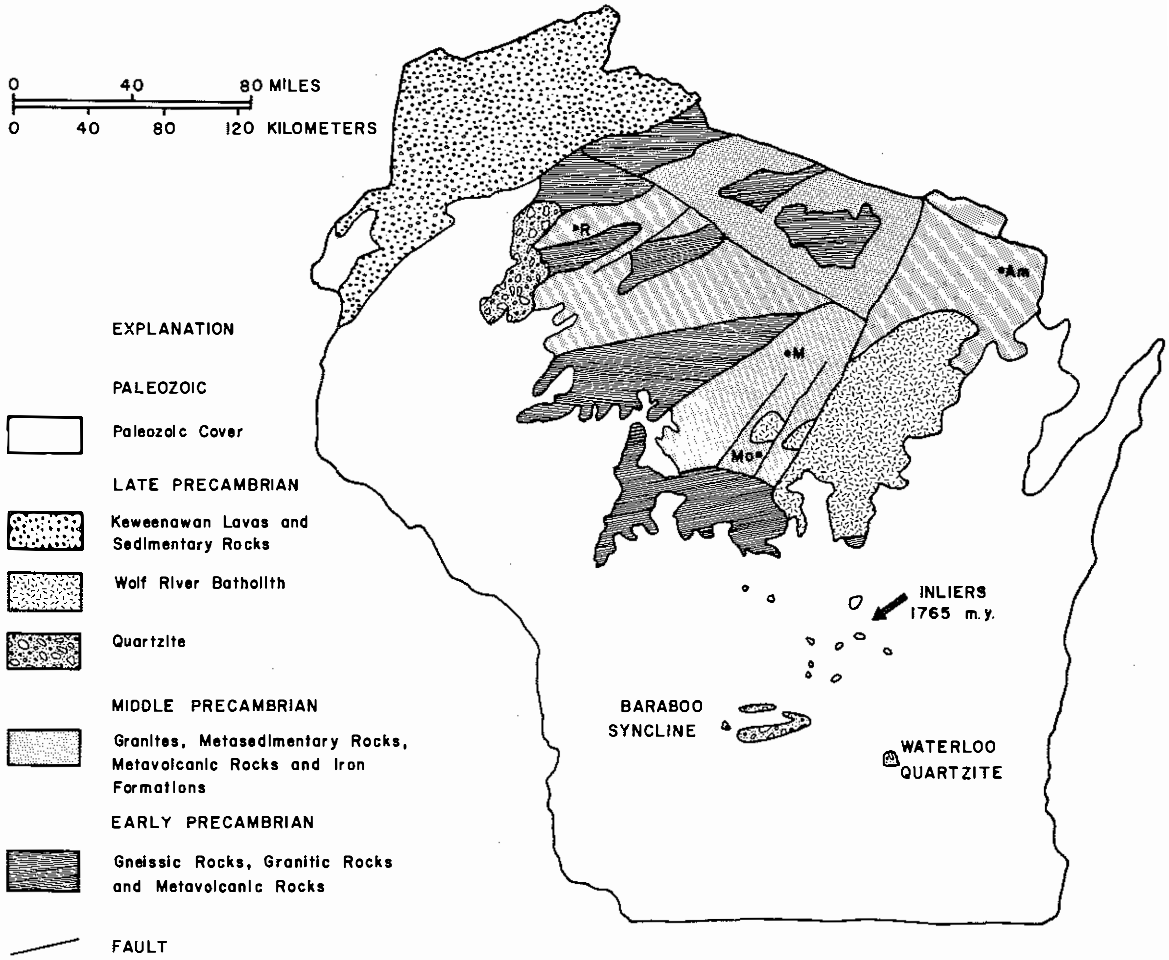

Figure 2. Location of Fox River Valley inliers. Other possible 1765 m.y. old exposures (Van Schmus and others, 1975b) include the Amberg Quartz Monzonite (AM), a granite near Monico (M), a granophyric granite near Mosinee (Mo), and a porphyritic granite at Radisson (R) (Van Schmus, Personal Communication). Geology of northern Wisconsin modified from Sims (1976) and LaBerge (1977) (From Smith, 1978a).

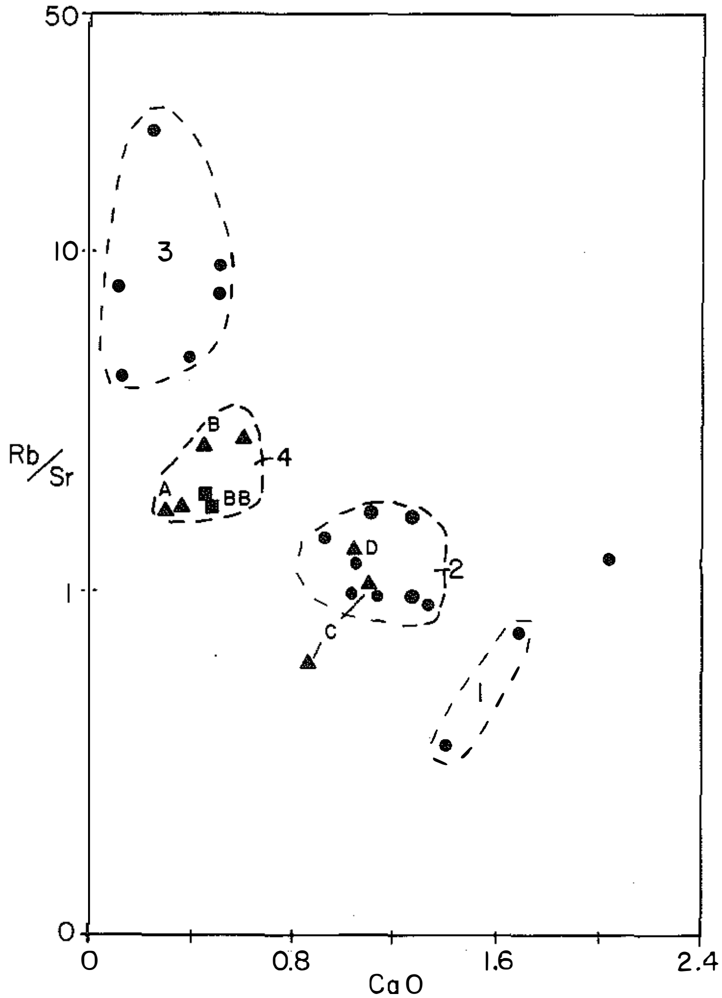

Figure 3. The rhyolites and granites in the Fox River Valley and Baraboo area can be divided into four groups on the basis of this CaO-Rb/Sr plot. Letters A-D represent Marcellon rhyolite units. BB is the Baraboo rhyolite. Unlabelled data point at about 2 percent CaO is Marquette unit C sample 91 (from Smith, 1978a).

New chemical data for the rhyolite and granite inliers (Smith, 1978a) divide the Fox River Valley and Baraboo rocks into four chemical groups (Figure 3): Group 1 - fine-grained granite at Baxter Hollow and a coarse-grained dike at Observatory Hill are characterized by high CaO ($\bar{x}$ = 1.58%) and low Rb/Sr ratio ($\bar{x}$ = 0.54); Group 2 - fine-grained and porphyritic rhyolite at the Marquette exposure and a fine-grained plagioclase-bearing rhyolite at the Marcellon inlier have intermediate CaO contents ($\bar{x}$ =1.22%), and Rb/Sr ratios ($\bar{x}$ = 1.01); Group 3 - porphyritic rhyolite and granophyric granite are characterized by low CaO ($\bar{x}$ = 0.40%), and high Rb/Sr ratios ($\bar{x}$ = 7.8); Group 4 - rhyolites at the Marcellon and Baraboo exposures are intermediate in chemistry between groups 2 and 3 ($\bar{x}_{CaO}$= 0.51%, $\bar{x}_{Rb/Sr}$= 1.53).

Chemical correlation and geologic mapping indicate that the chemical groups occur geographically as northeast trending bands across south-central Wisconsin

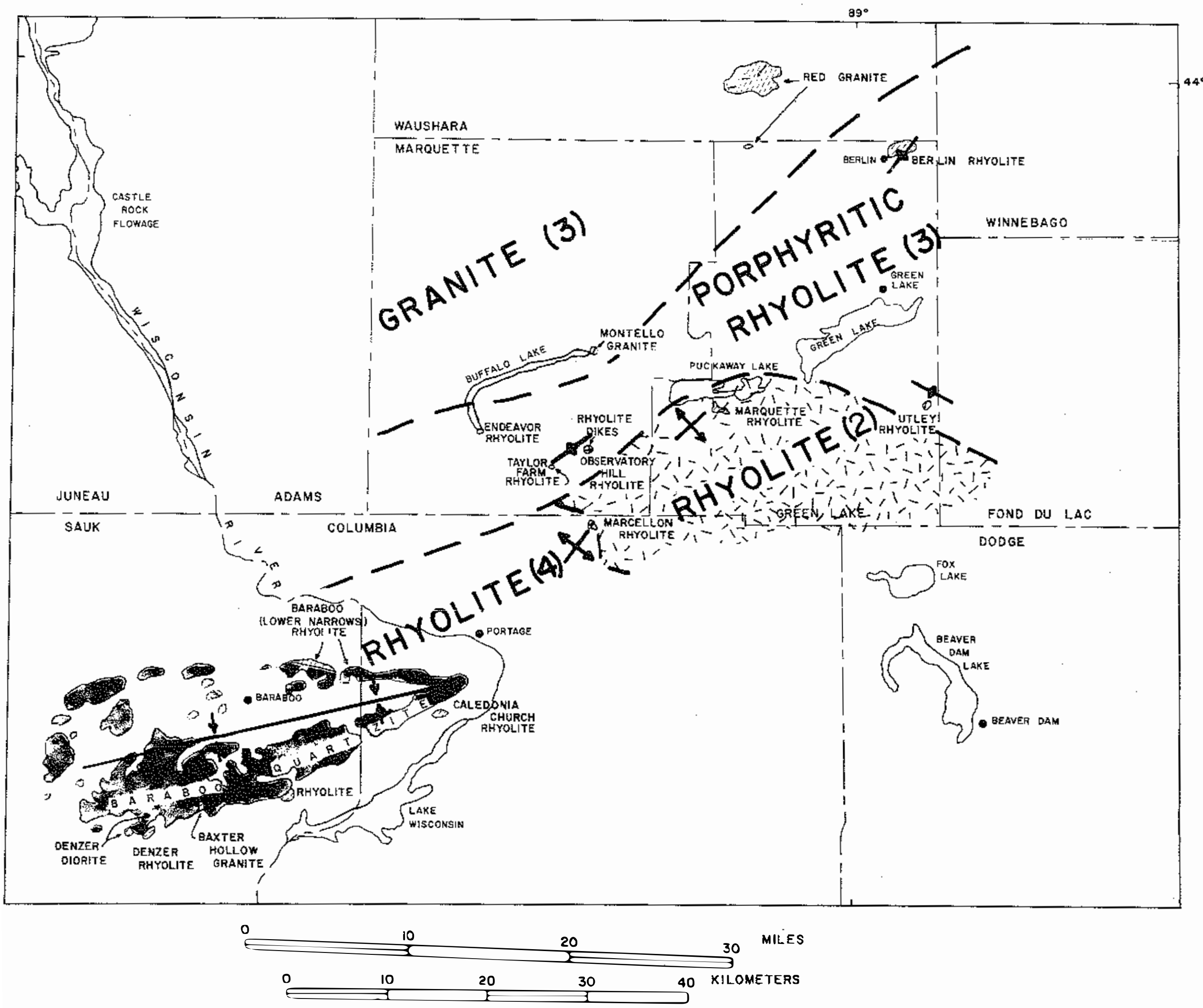

Figure 4. Map of the Fox River Valley-Baraboo area showing the geographic distribution of the chemical groups. Dashed lines are inferred contacts between chemical groups. Since these contacts parallel structures in exposures, patterns on this map probably reflect the geology of the buried Precambrian basement in this area. Foliation symbol indicates trend of banding in rhyolites, fold symbols indicate mean direction of axial plane traces, and shaded areas are outcrops of Baraboo Quartzite (from Smith, 1978a).

(Figure 4). Structural trends within the inliers parallel contacts between the chemical groups, suggesting that the chemical trends reflect the geology of a large area of buried Precambrian rock in south-central Wisconsin.

Historical Summary of Research on the Fox River Valley Inliers

The Fox River Valley igneous rocks were first described by Percival (1856) in the Annual Report of the Geological Survey of Wisconsin. He reported bedding in the rhyolites and probably regarded them as metasedimentary rocks. Chamberlin (1877 and Irving (1877) indicated that the origin of the rhyolite (their quartz-porphyry) in the Fox River Valley and the Baraboo area was in doubt, and suggested either an eruptive or metamorphic (metasedimentary) mode of formation for these rocks. Irving (1877) described several of the inliers in some detail and noted the parallel orientation of "bedding" in the quartzite and rhyolite inliers to the northeast. Accordingly, he placed the rhyolites (quartz-porphyry), quartzites and granites into "a great quartzite series". Both Chamberlin and Irving mistakenly interpreted the rhyolite at Baraboo as younger than the quartzite (they did not recognize the overturned nature of the north limb of the Baraboo syncline) and extended this age relationship to the inliers in the Fox River Valley.

Weidman (1895) correctly recognized the igneous nature of the rhyolites (his quartz-keratophyre) on the north range of the Baraboo syncline. Weidman (1898) also published accounts of the Berlin and Utley rhyolites, and presented the first chemical data for these rocks. Weidman (1904) demonstrated that quartzite lies stratigraphically above rhyolite in the Baraboo area by correctly interpreting the structural geometry of the Baraboo syncline. Buckley (1898) described quarrying operations in the Fox River Valley, especially at Montello, Utley and Marquette. In this work, he concentrated on the physical and visual properties of rocks in these quarries.

The most significant early contribution on the Fox River Valley inliers was made by Hobbs and Leith (1907). They mapped in some detail the Marcellon, Marquette, Observatory Hill, Montello and Endeavor inliers and described the chemical composition of these igneous rocks by providing 12 new chemical analyses made by W. W. Daniells. Part of their work was based on a B.S. thesis by W. W. Pretts (1895). Hobbs and Leith described a sequence of rock types passing from granite to the north through rocks of intermediate texture (the porphyritic rhyolites) to "typical surface volcanics" to the southeast. In the surface volcanics they recognized spherulites, perlitic fractures, axiolitic texture and brecciated rhyolite. Hobbs and Leith noticed the similarities in chemistry and mineralogy between the rhyolites and granites and suggested a genetic relationship between the two rock types. Alden (1918) reviewed pre-1918 research on the Precambrian and Pleistocene geology of south-central Wisconsin.

These early studies were followed by geologic investigations by Stark (1930, 1932) on the rhyolite and gabbro in the Baraboo range, and Gates (1942) on the Baxter Hollow Granite. In 1935 the area was visited by a field trip organized by the Kansas Geological Society (Leith, 1935). Asquith (1964) identified microscopic shard and axiolitic structures in the Fox River Valley and Baraboo rhyolites, and interpreted them as ash-flow tuffs. Dalziel and Dott (1970) observed faint shard-like relicts in the more deformed Baraboo rhyolites and concluded that most of the rhyolite section at Baraboo was composed of ash-flow tuffs. Abstracts by Smith and Hartlaub (1974), Smith (1975a and 1975b) and Smith (1976a) and a paper (Smith, 1978a) described the geology of the Marquette and Marcellon rhyolites, related rhyolites and granites between inliers and provided the first modern chemical data for these rocks.

The Fox River Valley igneous rocks were first dated by Goldich and others (1966) by the Rb-Sr technique at 1490 m.y. B.P. (for the Utley Rhyolite). This date is reported by Dott and Dalziel (1972) as 1.576 $\pm$ 70 m.y. B.P. Earlier, they (Dalziel and Dott, 1970) reported an age of 1540 m.y. B.P. for the Baraboo rhyolite. Van Schmus and others (1975b) published a Rb-Sr date of 1650 m.y. B.P. for the Fox River Valley igneous rocks, but were quick to point out in the same article that this age is probably low by at least 150 m.y. U-Pb dating indicated that the rocks are 1800 m.y. old (Van Schmus and others, 1975b). The 1650 m.y. old date was equated to a mild "hydrothermal" event (1630 m.y. B.P. in Van Schmus, 1978. Van Schmus, 1978 refined the U-Pb date on the Fox River Valley rocks by the addition of new data and the use of a new decay constant. The presently accepted date for the emplacement of these rhyolites and granites is 1765 $\pm$ 10 m.y. B.P.

THE BASEMENT

Introduction

Because exposures of Precambrian rock in south-central Wisconsin are widely separated, information about the Precambrian basement must be obtained from well cuttings, core and geophysical data. Chemical data and structures within the inliers can also be used to determine the distribution of basement rock types and to suggest the trend of basement structures.

Drill records and well cuttings for Wisconsin were first systematically examined and compiled by F. T. Thwaites. His results were published as surface contour maps of the buried Precambrian of Wisconsin in 1931, 1940, and in 1957. Dutton and Bradley (1970) refined the work of Thwaites by the addition of new deep well data. The maps presented here use the data of both Thwaites and Dutton and Bradley. In addition, new well data compiled by the Wisconsin Geological and Natural History Survey, and well data obtained by the author in the field during the summer of 1977 are incorporated into these maps.

Even though metric units are used throughout this report, English units are retained on the surface contour map and in discussion of the deep well data.

Basement Geological Map

The distribution of major rock types in the Precambrian basement of south-central Wisconsin is depicted in figure 5. Granite and quartzite are the dominant rock types. Rhyolite and mafic rocks are rarely found in well cuttings. Granites in the basement from Green Bay to Pewaukee are lithologically similar to those exposed in the Redgranite-Montello area. Granite in cuttings is characteristically a quartz, pink alkali feldspar, biotite-bearing rock with microscopic intergrowths of quartz and alkali feldspar. Similarities in lithology between exposed and buried granites suggest that there may be a large composite batholith of post-Penokean age (1765 m.y. old) under much of south-central Wisconsin. However, since it is common for granites of widely different ages to have a similar lithology, additional chemical, petrographic and geochronological information is required to confirm the existance of such a composite batholith. A biotite-rich, very fine-grained granite is found in well cuttings from the south margin of the Baraboo range to Sauk City. This granite is similar in lithology to the Baxter Hollow granite (Gates, 1942) and may represent a southward extension of this intrusion. Granite containing abundant muscovite is encountered near Appleton and Pewaukee. Granites are locally cut by gabbro and diroite dikes (?), particularly in the Madison area. The complexity of the Precambrian basement as revealed by closely spaced wells in the Madison area is probably typical of the Precambrian basement as a whole (Note - rhyolites identified by Thwaites in the Madison area are in fact fine-grained granites).

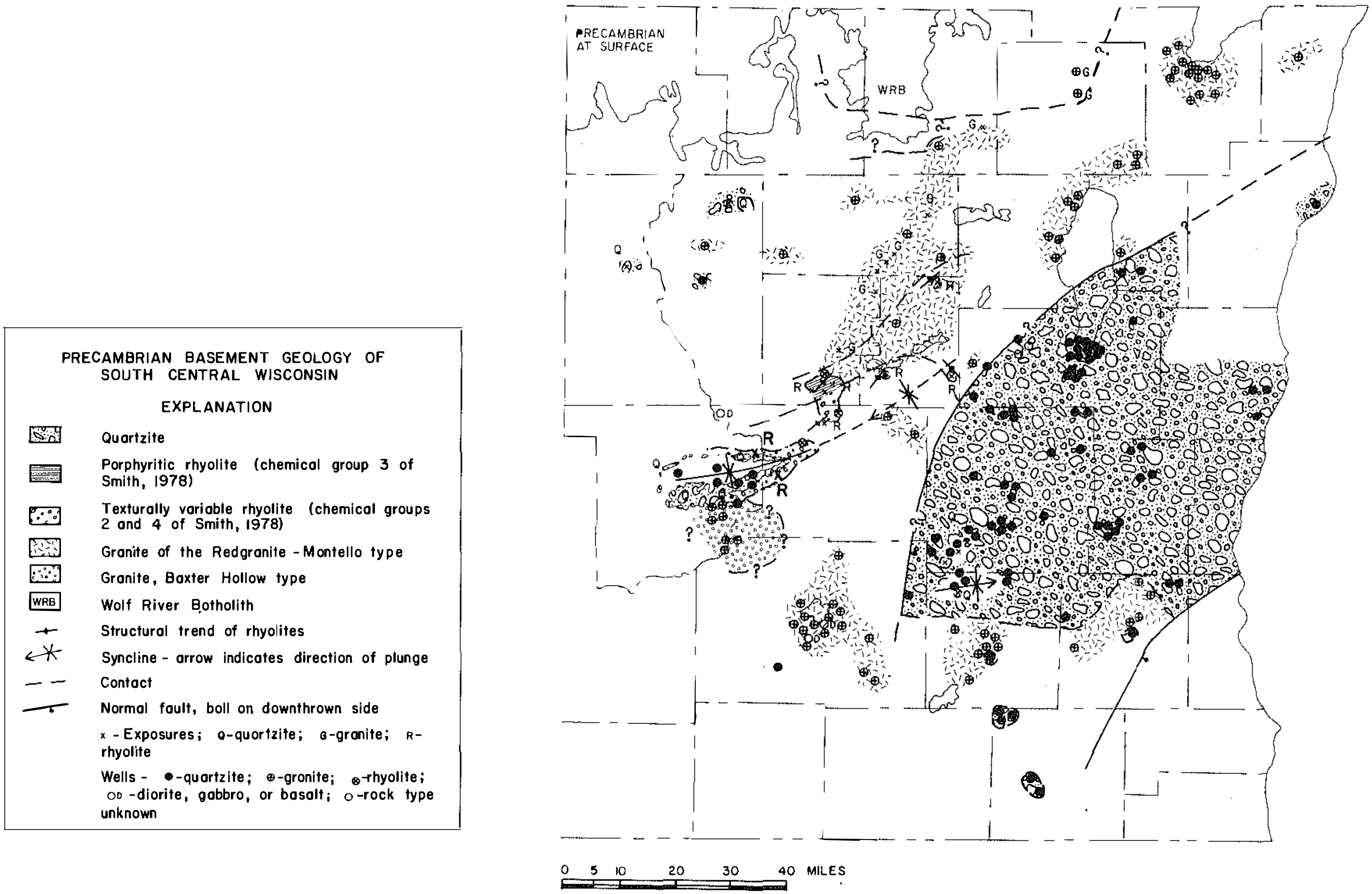

Figure 5. Precambrian basement geology map of south-central Wisconsin.

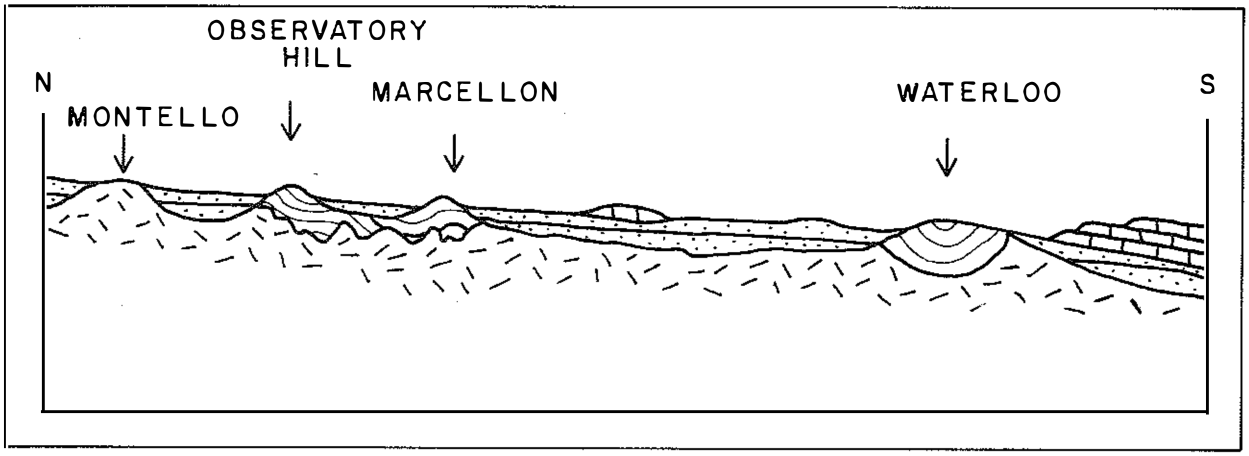

Figure 6. Schematic geologic section across south-central Wisconsin from Montello to Waterloo. Stippled pattern is the composite granite batholith. Folded patterns at Observatory Hill and Marcellon represent the rhyolite roof pendants. The Waterloo Quartzite is infolded into the granite basement. The Precambrian rocks are overlain by Cambrian and Ordovician sedimentary rocks.

Rhyolite is rarely encountered in deep wells except adjacent to rhyolite exposures. Rhyolite inliers are commonly surrounded by granite, suggesting that they are roof pendants within the granite batholith (Fig. 6). The shape of the rhyolite knobs (inliers) reflects the shape of the rhyolite roof pendants. Most of the rhyolite is fine-grained and dense, hence it is highly resistant to erosion. The surrounding granite is less resistant and trends to erode more easily than the rhyolite, thus leaving the rhyolite roof pendants as topographically high areas.

Quartzite occurs as a broad sheet of complex structure. In the Waterloo area there is a poorly exposed, east-plunging syncline (Buell, 1892; Warner, 1904). Quartzite overlies the igneous basement to the south, but in the west there may be a normal fault downthrown to the east separating quartzite from the igneous terrain.

To the west of Seymour in Outagamie County, a coarse-grained, alkali feldspar, biotite, blue-quartz granite was located in a well at a depth of 500 feet. This rock is similar in lithology to rocks of the Wolf River Batholith and especially to the Waupaca Rapikivi (Wiborgite) that crops out to the north of Waupaca (Van Schmus and others, 1975a). The Wolf River Batholith according to this information may extend as far to the east as Seymour. Since granite at Green Bay is of the Redgranite-Montello type, the contact between Wolf River granites and the older basement must run between Green Bay and Seymour.

Precambrian Surface Contour Map

The Precambrian surface slopes gently to the east, southeast and south off the Wisconsin arch (Fig. 7). This surface may be a peneplain, and because of the difference in contour spacing between northeast and south-central Wisconsin, Martin (1965) speculated that the surface may consist of two peneplains. Standing above this surface as monadnocks are ridges and knobs of resistant Precambrian

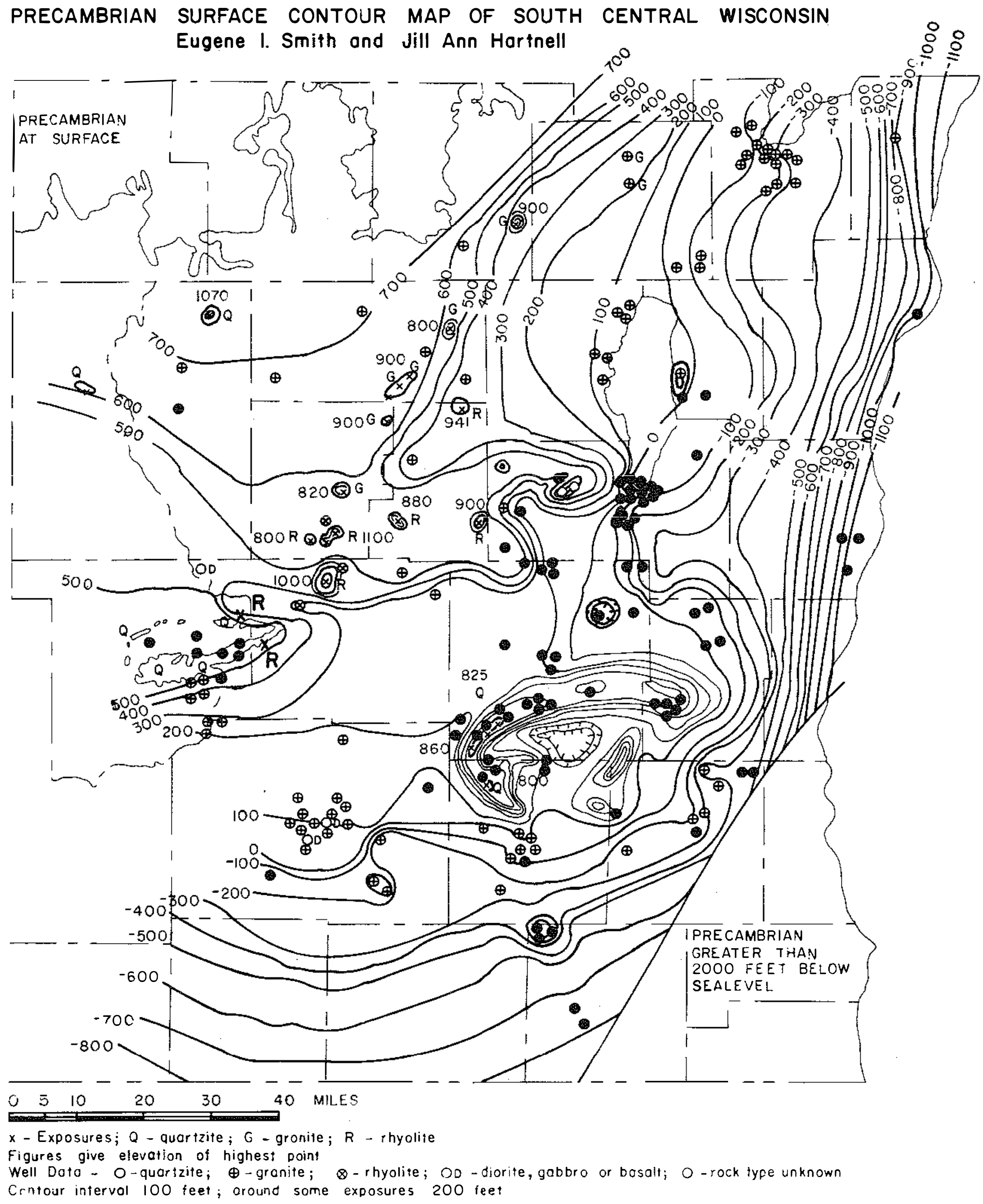

Figure 7. Surface contour map of the buried Precambrian basement of south-central Wisconsin.

rock. The majority of the known Precambrian topographic highs protrude through the Paleozoic and Pleistocene cover as inliers (for example, at Baraboo, in the Fox River Valley, and at Waterloo). In addition, there are at least four buried knobs of Precambrian rock in this area. Both the exposed and buried knobs rise quite abruptly from the peneplained Precambrian surface; for example, the rhyolite knob at Berlin stands over 600 feet above the surface. This change in elevation occurs over a lateral distance of only 1 km. Other Fox River Valley knobs have similar relief (Fig. 7).

The ridges of Quartzite that form the eastward plunging Waterloo syncline show clearly on the contour map. Surface contours of the Waterloo area are based on a geophysical study by Sumner (1956). The nose of the Waterloo fold is in the Portland area. The north limb extends from the Portland area to the east as far as Hartford in Washington County, and the south limb terminates abruptly near Fort Atkinson. The south limb may continue to Whitewater in Walworth County as indicated by a quartzite knob beneath that city (Fig. 7). The quartzite ridge may in fact continue to Delavan in central Walworth County.

Buried Precambrian knobs occur at Ripon (granite), Rosendale (rock type unknown), Brothertown (quartzite), Whitewater (quartzite) and Waupun (quartzite). Thwaites (1957) connected the Rosendale high to the Brothertown high to form the Fond du Lac quartzite range. Present data neither support nor refute the existence of this quartzite ridge. The buried knob at Hartford (described by Thwaites, 1957) is in fact part of the Waterloo range.

BRIEF COMMENT ON THE METAMORPHIC GRADE OF SOUTH-CENTRAL WISCONSIN PRECAMBRIAN ROCKS

The rhyolites and granites and overlying quartzites in south-central Wisconsin were metamorphosed in general to the lower greenschist facies. Dalziel and Dott (1970) suggest lower greenschist facies metamorphism for the Baraboo Quartzite on the basis of the occurrence of pyrophyllite in phyllite beds interlayered with the quartzite. This mineral is not stable at temperatures above 400 to 430° C at 1 to 3.9 kb pH_2O (Hemley, 1967; Kerrick, 1958). Weidman (1904) reports the "probable" presence of andalusite in the Seeley Slate (stratigraphically above the Baraboo Quartzite). This occurrence, if confirmed, would indicate that metamorphism reached the upper part of the greenschist facies.

The rhyolites also show the effects of a mild metamorphic event. Alkali feldspar is commonly altered to sericite, and plagioclase to sausserite. Mafic minerals are altered to epidote-clinozoisite and/or chlorite. In several specimens aligned grains of epidote, chlorite and secondary biotite penetrate the matrix. For the most part, however, the matrix of the rhyolites is unaltered; original pyroclastic textures are well preserved. Weidman (1904) suggested that rhyolites at Berlin and perhaps Utley were sheared and highly metamorphosed. Recent examination of these rocks indicates no evidence for high grade metamorphism, and suggests that Weidman may have mistaken primary flow foliation formed by flattened pumice for shear surfaces.

Recently identified in core from a well drilled at Waterloo (Haimson, 1978) are zones of phyllite rich in reddish-brown subhedral to anhedral andalusite porphyroblasts. In section the andalusite is broken and partially altered to sericite (Fig. 8). Some grains are cut by a weak penetrative foliation revealed

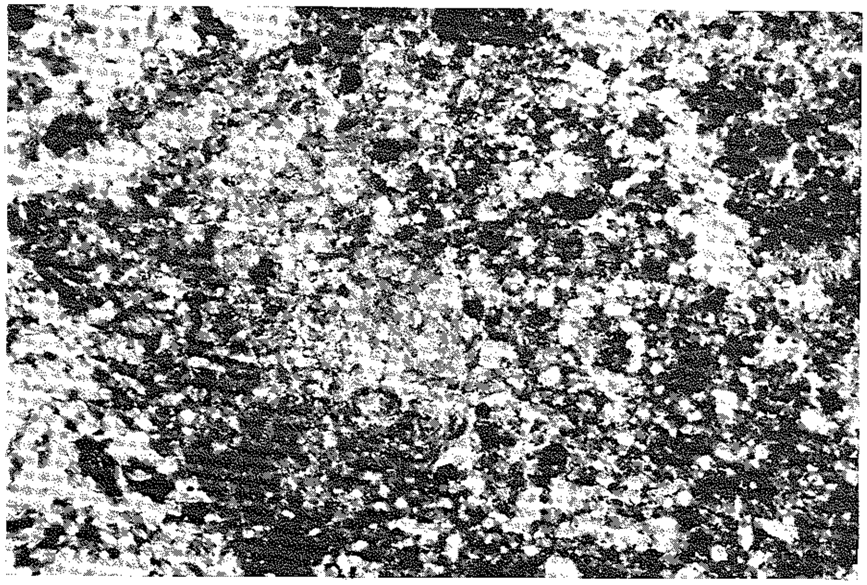

Figure 8. Photomicrograph of a subhedral andalusite porphyroblast in phyllite interbedded with the Waterloo Quartzite. The andalusite was recently identified in core from a deep diamond drill hole drilled by Haimson (1978). This porphyroblast is entirely altered to sericite. Several andalusite grains, however, retain unaltered cores. Bar scale is 1 mm.

by aligned sericite grains. The assemblege andalusite-muscovite-quartz suggests that metamorphism reached upper greenschist facies in the Portland area. The foliation that cuts the andalusite may reflect a later retrograde overprint. A shallow intrusion is perhaps responsible for this zone of higher grade metamorphism (a thermal node?).

GEOLOGIC HISTORY

The major late- and post-Penokean aged events in south-central Wisconsin are (stops refer to field trip stops of Smith, 1978c):

1) Intrusion of granite (stop 1) and extrusion of genetically related ash-flow tuffs (stop 2).

2) Eruption of the texturally variable ash-flow tuffs (stops 3 and 4). Granite formed in step 1 probably continued to rise, engulfing most of its volcanic cover and leaving surviving rhyolites as roof pendants.

3) Deposition of sediments on a eroded volcanic-plutonic terrain. Later, folding and low grade metamorphism resulted in the Baraboo and Waterloo synclines and the folding of the rhyolite ash-flow tuffs.

An alternate, more complex interpretation of the structural geometry of this terrain involves two episodes of folding. Notice that the prominent bend in the contact between chemical groups 2 and 3 (south of Green Lake) is mirrored by a change in the orientation of structural elements in the rhyolite inliers (Fig. 5). At Marquette, fold axes trend N. 30 to N. 50 E., but at Utley, fold axes and flow foliation strike N. 70° W. (Gram, 1947). It is tempting to extend the axis of the Baraboo syncline into this area to account for this structural bend. More than one episode of folding would be required to explain this structural geometry. During the first episode of deformation the rhyolites were folded. The second episode involved the refolding of episode 1 structures and the formation of the Baraboo and Waterloo synclines. These events were separated by a period of erosion and the deposition of the Baraboo-Waterloo sandstone sheet. If this history is correct, an uncomformable relationship would be expected between quartzite and underlying rhyolite. The only area where this hypothesis can be tested is in the Baraboo range where both rock types crop out in close proximity. On the north side of the Baraboo range, to both the east and west of the Lower Narrows of the Baraboo River, abundant outcrops of rhyolite are found structurally above but stratigraphically below the quartzite (the north limb of the syncline is overturned in this area, Dalziel and Dott, 1970). To the west of the narrows, the rhyolite strikes N. 40 E. and the quartzite trends east-west to N. 80° W. To the east of the narrows, flow banding in the rhyolites varies in strike from N. 40° to N. 80° E., while the quartzite trends N. 80° E. to N. 80° W. At the Caledonia Church locality (Fig. 1) banded and brecciated rhyolite is overlain by Baraboo Quartzite on the south limb of the syncline. Here the rhyolite strikes N. 80° E. and the quartzite trends N. 40° to N. 60° E. These structural data are suggestive of an unconformity between the quartzite and rhyolite at Baraboo and strongly support a model that involves at least two folding events to describe the structural evolution of this area.

4) Intrusion of the coarse-grained rhyolite dikes (stop 2), and the Baxter Hollow Granite (in the Baraboo area). Also intrusion of dacite, andesite and basalt dikes (stops 1 and 4). Dacite dikes are younger than andesite dikes at Marquette, and at Marcellon an andesite dike is younger than a basalt dike. These relationships suggest that the age sequence for the dikes from youngest to oldest is dacite, andesite, basalt. Dike emplacement may have been penecontemporaneous with the events of step 3. The thermal node (?) in the Portland area and an amphibolite dike that cuts Waterloo Quartzite (identified in well core) are additional evidence for igneous activity during this stage.

5) Local intrusion of pegmatite dikes into the Waterloo Quartzite.

Events 1 and 2 occurred 1765 $\pm$ 10 m.y. ago. Events 3 and 4 probably occurred 1630 m.y. ago, and step 5, 1500 m.y. ago, contemporaneous with the intrusion of the Wolf River Batholith(?).

Hopefully these comments on the igneous and metasedimentary rocks in south-central Wisconsin will rejuvenate interest in these important exposures and will stimulate professional geologists and students to study these rocks with the care and detail that they deserve.

REFERENCES CITED

Alden, W. C., 1918, The Quaternary geology of southeastern Wisconsin: U. S. Geol. Survey Prof. Paper 106, 356 p.

Asquith, G. B., 1964, Origin of the Precambrian Wisconsin rhyolites: Jour. Geol., v. 72, p. 835-847.

Banks, P. O., and Cain, J. A., 1969, Zircon ages of Precambrian granitic rocks, northeastern Wisconsin: Jour. Geol., v. 77, p. 208-220.

Buckley, E. R., 1898, Building and ornamental stones of Wisconsin: Wisc. Geol. and Nat. History Survey Bull. 4, 544 p.

Buell, I. M., 1892, Geology of the Waterloo Quartzite area: Wisc. Acad. Sci. Arts and Letters Trans., v. 9, p. 225-274.

Chamberlin, T. C., 1877, The geology of eastern Wisconsin: in the Geology of Wisconsin, Survey of 1873-1877, v. 2: Wisc. Geol. Survey, p. 95-405.

Dalziel, I. W. D., and Dott, R. H., 1970, Geology of the Baraboo district, Wisconsin: Wisc. Geol. and Nat. History Surv. Info. Circular 14, 164 p.

Dott, R. H., and Dalziel, I. W. D., 1972, Age and correlation of the Precambrian Baraboo Quartzite of Wisconsin: Jour. Geology, v. 80, no. 5, p. 552-568.

Dutton, C. E., and Bradley, R. E., 1970, Lithologic, geophysical, and mineral commodity maps of Precambrian rocks in Wisconsin: U. S. Geol. Surv. Misc. Inv. Map I-631.

Gates, R. M., 1942, The Baxter Hollow granite cupola: Am. Min., v. 27, no. 10, p. 699-711.

Goldich, S., Lidiak, E. G., Hedge, C. E., and Walthall, R. G., 1966, Geochronology of the midcontinent region, United States-Part 2. Northern area: Jour. Geophys. Res., v. 71, p. 5389-5408.

Gram, O. E., 1947, Tectonic features of the Utley metarhyolite: Jour. Geol., v. 55, p. 427-438.

Haimson, B. C., 1978, Engineering geology, stress regime and mechnical properties of some Precambrian rocks in south-central Wisconsin: Geoscience Wisc. Vol. 2 (this issue).

Hemley, J. J., 1967, Stability relations of pyrophyllite, andalusite and quartz at elevated pressures and temperatures (abs.): Trans. Am. Geophys. Union, v. 48, p. 224.

Hobbs, W. H., and Leith, C. K., 1907, The Precambrian volcanic and intrusive rocks of the Fox River Valley, Wisconsin: Univ. Wisc. Bull. 158, Sci. Series, v. 3, no. 6, p. 247-277.

Irving, R. D., 1877, The Geology of Central Wisconsin: in the Geology of Wisconsin, Survey of 1873-1877, v. 2: Wisc. Geol. Surv., p. 409-642.

Kerrick, D. M., 1968, Experiments on the upper stability limit of pyrophyllite at 1.8 kb and 3.9 kb water pressure: Am. Jour. Sci., v. 266, p. 204-214.

LaBerge, G. L., 1977, Major structural features in central Wisconsin and their implications on the Animikie Basin (abs.): Proceedings of the 23rd Annual Institute on Lake Superior Geology, p. 23.

Leith, A., 1935, The Precambrian of the Lake Superior region, the Baraboo District, and other isolated areas in the upper Mississippi Valley: in Kansas Geol. Soc. Guidebook, Ninth Annual Field Conference, p. 320-322.

Martin, L., 1965, The Physical Geography of Wisconsin: Univ. Wisc. Press, 608 p. (reprinted from Wisc. Geol. and Nat. History Survey Bull. 36, 1932).

Percival, J. G., 1856, Annual Report of the Geological Survey of Wisconsin: Wisc. Geol. Survey, p. 105-106.

Pretts, W. W., 1895, On the area of eruptive rocks near Marquette, Wisconsin: Madison, Wisconsin Univ. B. Sc. thesis, 31 p.

Sims, P. K., 1976, Precambrian tectonics and mineral deposits, Lake Superior region: Econ. Geology, v. 71, p. 1092-1127.

Smith, E. I., 1975a, Chemical characteristics of the Marquette rhyolite, Green Lake County, Wisconsin (abs.): Geol. Soc. America, Abstracts with Programs, v. 7, no. 6, p. 860.

Smith, E. I., 1975b, Mineralogy and chemistry of the Precambrian Marquette rhyolite, Green Lake County, Wisconsin (abs.): Proceedings of the 21st Annual Institute on Lake Superior Geology, p. 9.

Smith, E. I., 1976a, Geology and geochemistry of the Precambrian Marcellon rhyolite, Columbia County, Wisconsin (abs.): Proceedings of the 22th Annual Institute on Lake Superior Geology, p. 58.

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

Smith, E. I., 1978c, Precambrian inliers in south-central Wisconsin: Wisc. Geol. and Nat. History Surv. Field Trip Guide Book No. 2.

Smith, E. I., and Hartlaub, D. E., 1974, Precambrian Marquette rhyolite, Green Lake County, Wisconsin: volcanic stratigraphy, petrography, and flow direction determinations (abs.): Geol. Soc. America, Abstracts with Programs, v. 6, no. 6, p. 546.

Stark, J. T., 1930, Precambrian water-laid tuff in the Baraboo, Wisconsin, district: Jour. Geol., v. 38, p. 466-471.

Stark, J. T., 1932, Igneous rocks of the Baraboo district, Wisconsin: Jour. Geol., v. 40, p. 119-139.

Sumner, J. S., 1956, Geophysical studies on the Waterloo Range, Wisconsin: Madison, Wisconsin Univ., Ph.D. thesis, 71 p.

Thwaites, F. T., 1931, Buried Precambrian of Wisconsin: Geol. Soc. America Bull., v. 42, p. 719-750.

Thwaites, F. T., 1940, Buried Precambrian of Wisconsin: Wis. Acad. Sci. Arts and Letters Trans., v. 32, p. 233-242.

Thwaites, F. T., 1957, Buried Precambrian of Wisconsin: Wis. Geol. and Nat. Hist. Survey Map.

Van Schmus, W. R., 1976, Early and middle Proterozoic history of the Great Lakes area, North America: Phil. Trans. R. Soc. London, v. 280, p.605-628.

Van Schmus, W. R., 1978, Geochronology of the southern Wisconsin rhyolites and granites: Geoscience Wisconsin Vol. 2 (this issue).

Van Schmus, W. R., Medaris, L. G., and Banks, P. O., 1975a, Geology and age of the Wolf River Batholith, Wisconsin: Geol. Soc. America Bull., v. 86, p. 907-914.

Van Schmus, W. R., Thurman, E. M., and Peterman, A. E., 1975b, Geology and Rb-Sr chronology of Middle Precambrian rocks in eastern and central Wisconsin: Geol. Soc. America Bull., v. 86, p. 1255-1265.

Warner, J. H., 1904, The Waterloo Quartzite area of Wisconsin: Madison, Wisconsin Univ., B. A. thesis.

Weidman, S., 1895, On the quartz keratophyre and associated rocks of the North Range of Baraboo Bluffs: Wis. Univ. Bull., science series, v. 1, p. 35-56.

Weidman, S., 1898, Precambrian igneous rocks of the Fox River Valley, Wisconsin: Wis. Geol. and Nat. History Surv. Bull. 3, 63 p.

Weidman, S., 1904, The Baraboo iron-bearing district of Wisconsin: Wis. Geol. and Nat. History Surv. Bull. 13, 190 p.

GEOCHRONOLOGY OF THE SOUTHERN WISCONSIN RHYOLITES AND GRANITES

by

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INTRODUCTION

The rhyolitic and granitic rocks of southern Wisconsin comprise the southern-most exposures of Middle Precambrian igneous rocks in the Great Lakes area (Goldich and others, 1966). These rocks consist predominantly of rhyolitic volcanic rocks and granophyric granites (Smith, 1978) and as such are generally quite different from the volcanic and plutonic rocks of the Penokean complex in central and northern Wisconsin (Van Schmus and others, 1975). Instead, the southern Wisconsin rocks may represent the northern edge of a more extensive granite-rhyolite terrane present in the subsurface of the midcontinent region (Lidiak and others, 1966). Consequently, it is important to understand the age, tectonic setting, and petrogenesis of this key rock suite.

This report summarizes recent results obtained on the age of this suite of rocks. It is based largely on material contained in a more comprehensive study of the ages of Middle Precambrian rocks in Wisconsin (Van Schmus, in prep.). Sample numbers referred to below are from that report; detailed locations, analytical details, and analytical data on these and several related samples will be included there, and only the data for the southern Wisconsin suite proper are repeated here. All ages reported here are based on the decay constants recently recommended for international adoption (Steiger and 1977): λ (Rb-87) = 1.42×10^{-11} yr^{-1}; λ(U-235) = 9.85×10^{-10} yr^{-1}; and λ(U-238) = 1.551×10^{-10} yr^{-1}.

EARLIER RESULTS

Rb-Sr analyses on metavolcanic and granitic rocks from southern Wisconsin have been reported previously by Bass (1959), Goldich and others (1966), Dott and Dalziel (1972), and Van Schmus and others (1975). Reported ages on individual samples ranged from 1420 m.y. to 1725 m.y. This spread in ages was mainly due to two factors: (a) Goldich and others (1966) used a 47 m.y. half-life for Rb-87 while most other reports used a 50 m.y. half-life (the newly recommended value of the decay constant corresponds to a half-life of 48.8 m.y.), and (b) most of the samples have undergone variable losses of radiogenic Sr-87. Geologically, the second reason is more important. Furthermore, Van Schmus and others (1975) showed that these losses were systematic, such that results from the Fox River Valley rhyolites yielded an excellent isochron with an apparent age of 1630 ± 40 m.y. (Fig. 1).

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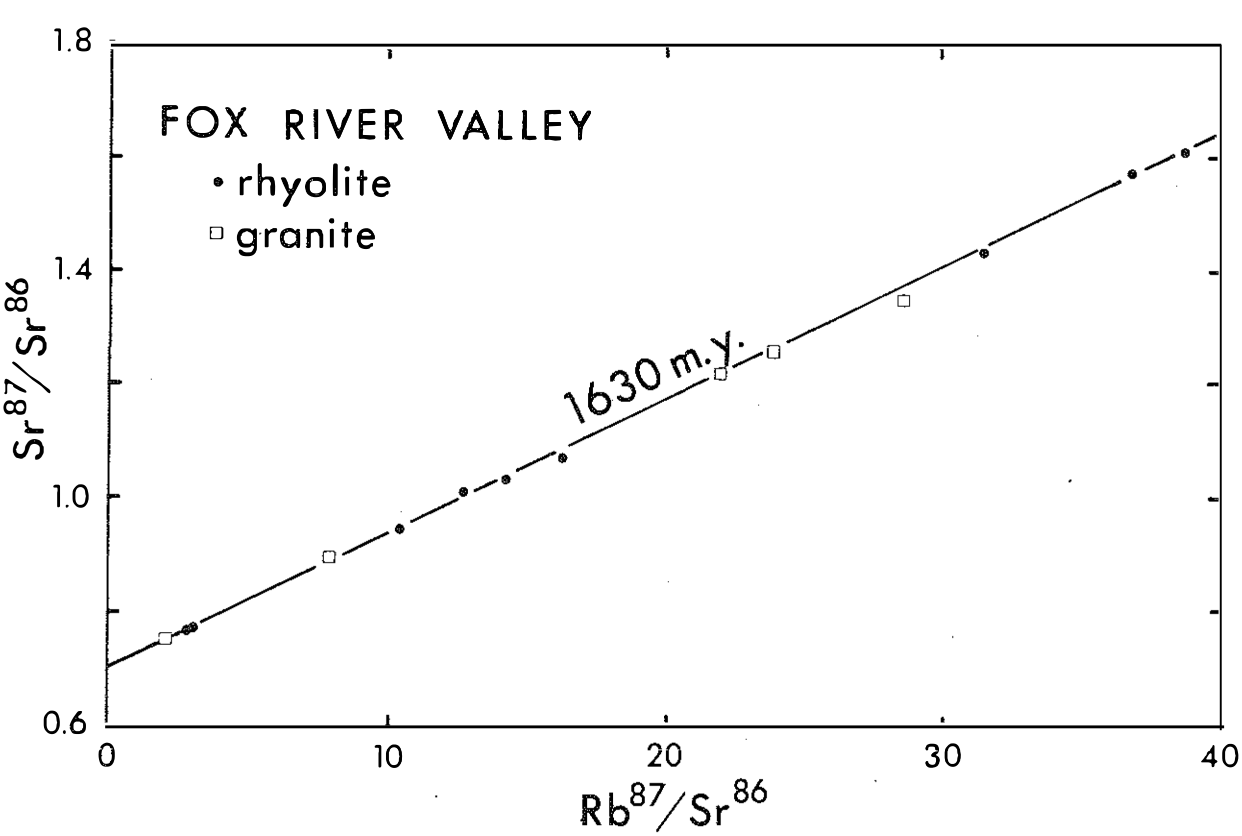

Figure 1. Rb-Sr diagram showing data obtained from granite and rhyolite of the Fox River Valley (Van Schmus and others, 1975). The isochron shown is that defined by the rhyolite alone and yields an apparent age of 1630 ± 40 m.y. with initial Sr-87/Sr-86 = 0.7046 ± 0.0043. The U-Pb age for these rocks is 1760 ± 10 m.y. (see text).

ZIRCON U-PB RESULTS

Zircons have been separated from three rhyolite samples and one granite sample: rhyolite from the Noble quarry near Marquette (sample 1, Table 1 and Figs. 2 and 3), rhyolite from the quarry at Utley (sample 2), rhyolite from Observatory Hill (sample 3), and granite from the quarry in Montello (sample 3). Details on the geology of these localities may be found in the report by Smith (1978) and references therein. All the rhyolite samples contain abundant quartz phenocrysts, a key indicator to the presence of separable zircons in rhyolite. The zircon populations from all samples consist of clear, euhedral crystals having sharp crystal face boundaries and no sign of alteration or relict cores. Ages derived from these samples will therefore represent primary crystallization ages and, hence, the virtual time of extrusion of the rhyolites or emplacement of the granite.

The U-Pb data from the individual zircon fractions (Table 1) define an excellent chord on a U-Pb diagram (Fig. 2). A least squares fit to the data yields an intersection with concordia of 1760 ± 10 m.y. (95% C.L.), which is taken as the crystallization age of the zircon suite and, thus, the true age of the rocks.

Table 1. Analytical data on separated zircon fractions

Sample No.	Zircon Frac.*	Concentrations U(ppm)	Pb(ppm)	Measured Pb Isotope Ratios# 204/206	207/206	208/206	Measured U/Pb, Pb/Pb Ratios& 206/238	207/235	207/206
1	total	847	274	0.00217	0.1360	0.1834	0.2748	4.031	0.1064
2	A	469	158	0.00215	0.1368	0.1824	0.2854	4.228	0.1075
3	A	471	137	0.00198	0.1333	0.1991	0.2445	3.583	0.1063
	B	758	199	0.00330	0.1495	0.2357	0.2081	2.996	0.1044
19	A	352	112	0.00063	0.1159	0.1258	0.2945	4.357	0.1073
	B1	386	127	0.00149	0.1271	0.1581	0.2900	4.357	0.1073
	C	484	151	0.00110	0.1223	0.1531	0.2795	4.135	0.1073

* A = least magnetic fraction; B,C = more magnetic fractions; B1 denotes 100-200 mesh sieve fraction for respective magnetic split.

Corrected for analytical blank. & Corrected for non-radiogenic Pb.

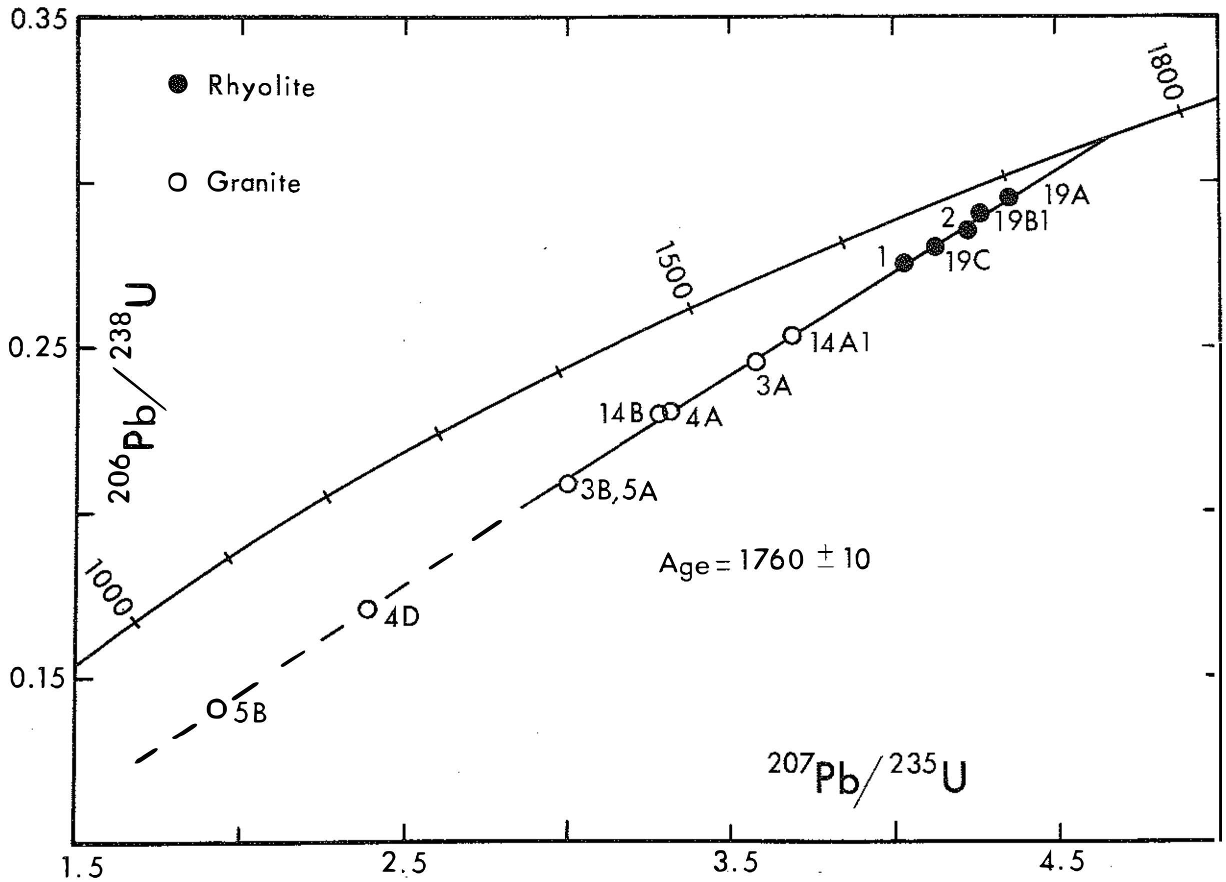

Figure 2. U-Pb plot of zircons from the rhyolite-granite suite of southern Wisconsin (samples 1, 2, 3, and 19; Table 1) and other apparently coeval plutonic rocks from northern Wisconsin (samples 4, 5, 14; Van Schmus, in prep.). The chord defined by data from the rhyolite and related granophyric granite intersects concordia at 1760 ± 10 m.y. (least squares fit at 95% C.L.).

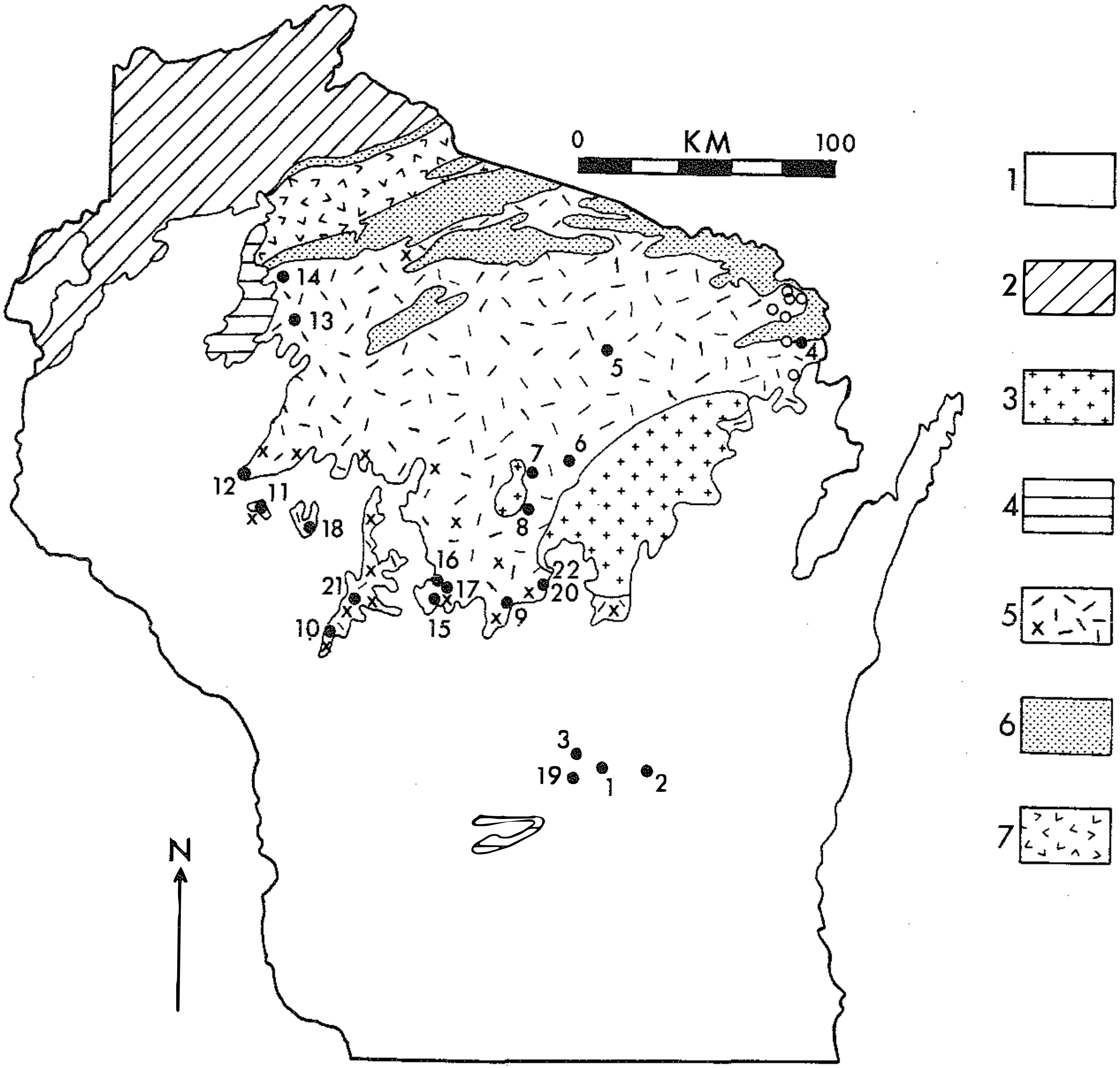

Figure 3. Generalized geologic map of Wisconsin showing major Precambrian terranes and distribution of units for which U-Pb analyses on separated zircons are available. From Van Schmus (in prep.). Unit 1, undifferentiated Paleozoic and younger rocks; Unit 2, Keweenawan igneous and sedimentary rocks; Unit 3, Wolf River Batholith; Unit 4, Baraboo and Barron Quartzites; Unit 5, undifferentiated igneous and metamorphic rocks, contains Penokean plutonic complexes, remnants of middle Precambrian metavolcanic and metasedimentary rocks, and remnants or windows of Archean gneiss and migmatite (denoted by 'x' where known); Unit 6, Middle Precambrian metavolcanic and metasedimentary rocks ca. 1850-1950 m.y. old; Unit 7, Archean basement rocks. Numbered dots are sample localities and numbers from Van Schmus (in prep.).

Several granitic plutons from northern Wisconsin contain zircons that yield U-Pb data which also fall on the chord defined by the southern Wisconsin rhyolite and granite samples (Van Schmus, in prep.; Fig. 2). These units are therefore essentially the same age, as, but petrographically distinct from the southern Wisconsin rocks. The northern Wisconsin units concerned are the Amberg Quartz Monzonite (Van Schmus and others, 1975; sample 4 on Fig. 3), granite south of Monico (Van Schmus and others, 1975; sample 5 on Fig. 3), and porphyritic granite from Radisson (sample 14 on Fig. 3). The relationship of these units to the southern Wisconsin rocks in terms of regional petrogenesis remains to be worked out, but one possible explanation is that they represent the deeper-seated counterparts of the rhyolite and granite to the south, and that the 1760 m.y. old igneous activity may have occurred throughout the Penokean complex in Wisconsin.

DISCUSSION

The problem of the Rb-Sr versus the U-Pb age in general for volcanic rocks has been discussed elsewhere (Van Schmus and others, 1975; Van Schmus, 1976; Bickford and Mose, 1975). The principal question here is whether the 1630 m.y. Rb-Sr age obtained from a large variety of rocks in the southern Lake Superior region, including the southern Wisconsin suite, has geological significance. At present there is no clear-cut answer, but my prejudice is that the age represents a definite event such as (a) a distinct post-volcanic (and post-quartzite) deformational and metamorphic event, or (b) sudden epirogenic uplift of the region. I believe it represents a distinct event because of the well defined isochron formed by the data and other well-defined 1630 m.y. systematics for Rb-Sr systems throughout the Lake Superior area (see Van Schmus, 1976) in contrast to the case in other regions where disturbed Rb-Sr systems do not yield coherent isochrons (for example Bickford and Mose, 1975). The fact that most of the rhyolites, including the overlying quartzite, are tectonically deformed (Dott and Dalziel, 1972; Smith, 1978) would tend to indicate that the 1630 m.y. age is associated with a distinct tectonic event.

At present the full regional significance of either the 1760 m.y. primary age or the 1630 m.y. metamorphic age for these rocks is unclear. There is insufficient geologic information from adjacent terranes, particularly to the south and west, to determine whether either age is related to a major crustal event (orogenic belt) or whether it is a more local phenomenon. Continued research in these areas over the next decade will hopefully clarify many of these questions.

ACKNOWLEDGMENTS

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REFERENCES CITED

Bass, M. N., 1959, Mineral age measurements-Wisconsin: Carnegie Inst. Washington Year Book 58, pp. 246-247.

Bickford, M. E., and Mose, D. G., 1975, Geochronology of Precambrian rocks in the St. Francois Mountains, southeastern Missouri: Geol. Soc. America Special Paper 165, 48 p.

Dott, R. H., and Dalziel, I. W. D., 1972, Age and correlation of the Precambrian Baraboo Quartzite of Wisconsin: Jour. Geol., v. 80, pp. 552-568.

Goldich, S. S., Lidiak, E. G., Hedge, C. E., and Walthall, F. G., 1966, Geochronology of the midcontinent region, United States. Part 2. Northern area: Jour. Geophys. Res., v. 71, pp. 5389-5408.

Lidiak, E. G., Marvin, R. F., Thomas, H. H., and Bass, M. N., 1966, Geochronology of the midcontinent region, United States. Part 4. Eastern area: Jour. Geophys. Res., v. 71, pp. 5427-5438.

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

Steiger, R. H., and Jäger, E., 1977, Subcommission on geochronology--Convention on the use of decay constants in geo- and cosmochronology: Earth Plan. Sci. Lett., v. 36, pp. 359-362.

Van Schmus, W. R., 1976, Early and middle Proterozoic history of the Great Lakes area, North America: Royal Soc. London Philos. Trans., Ser. A, v. 280, pp. 605-628.

Van Schmus, W. R., (in prep.), Chronology of igneous rocks associated with the Penokean Orogeny in Wisconsin: submitted for Geol. Soc. America Special Paper--Goldich Volume.

Van Schmus, W. R., Thurman, M. E., and Peterman, Z. E., 1975, Geology and Rb-Sr chronology of middle Precambrian rocks in eastern and central Wisconsin: Geol. Soc. America Bull., v. 86, pp. 1255-1265.

ENGINEERING GEOLOGY, STRESS REGIME AND MECHANICAL PROPERTIES OF SOME PRECAMBRIAN ROCKS IN SOUTH CENTRAL WISCONSIN

by

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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.

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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.

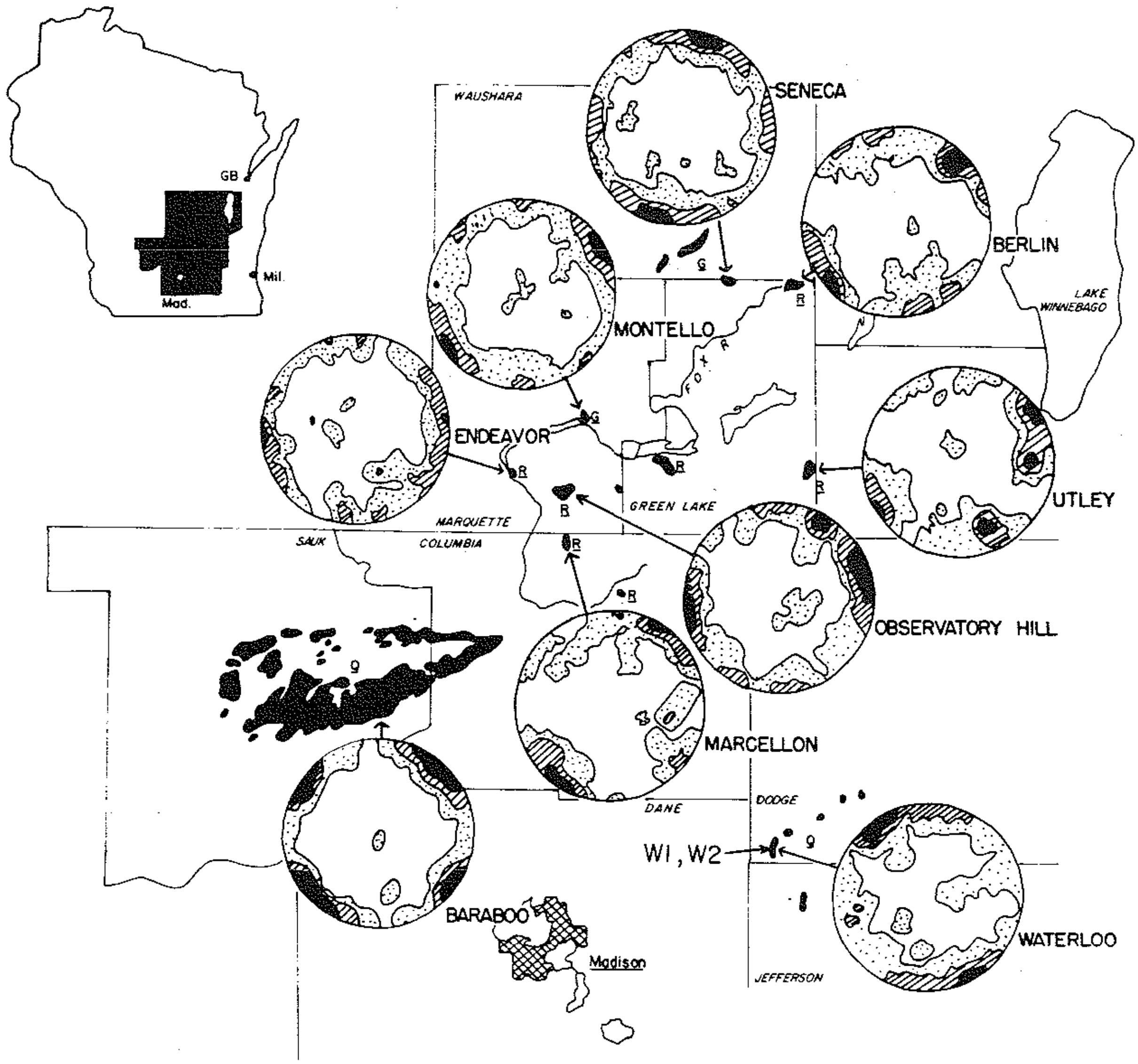

Figure 1. Locations of Precambrian rock outcrops in south-central Wisconsin with stereographic projections of joint data; 1, 5, 10% contours (rock types are: Q - quartzite, R - rhyolite, G - granite). Also shown is the location of the W1 and W2 core holes in the Waterloo quartzite.

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. ± 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.

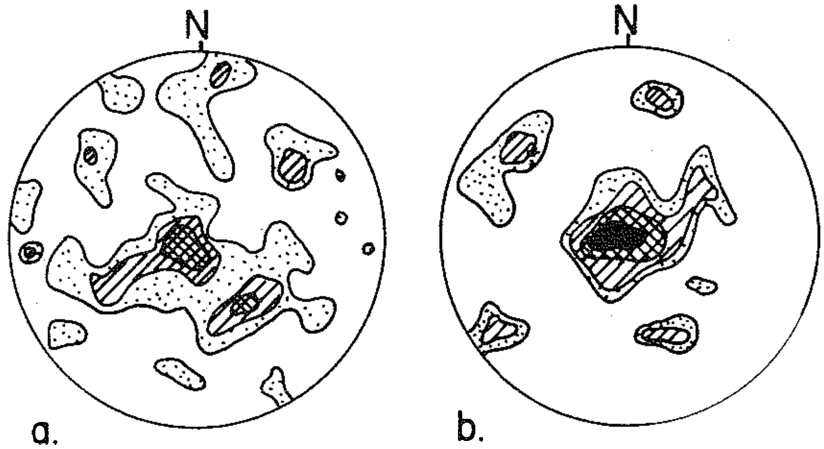

Figure 2. Equal-area plot of joints in the borehole at Montello: (a) chlorite coated joints; (b) iron-oxide coated joints. Contour intervals 2, 4, and 8 percent.

Waterloo Quartzite - 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.

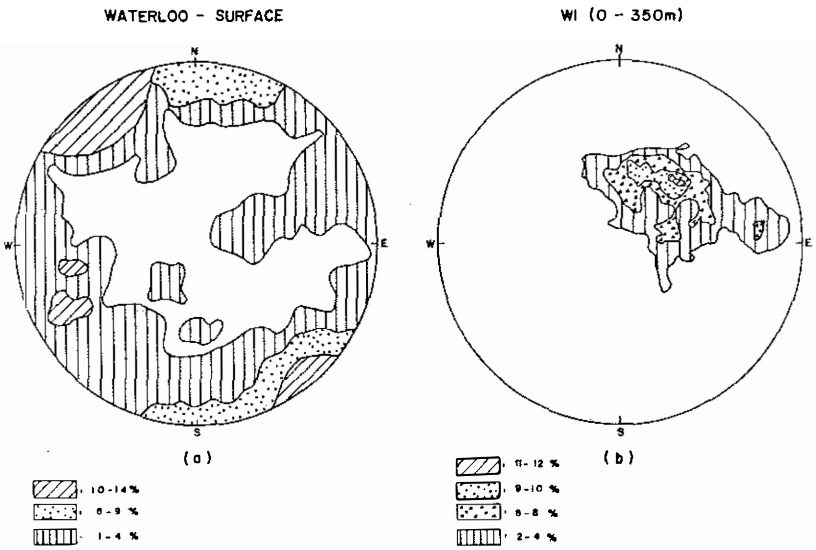

Figure 3. Equal-area plots of joints near Waterloo: (a) on surface; (b) in hole W1

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.

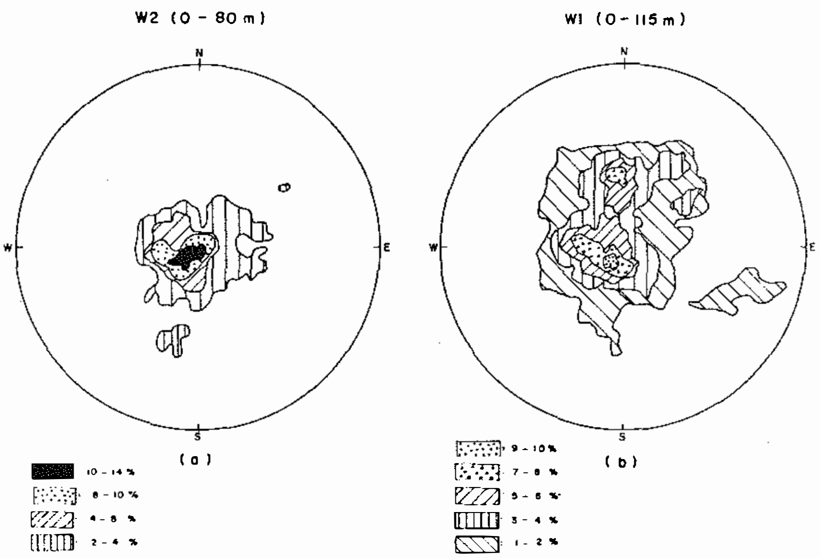

Figure 4. Equal-area plots of joints near Waterloo: (a) in hole W2; (b) in the top 115 m of hole W1.

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 ± 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). σ_{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).

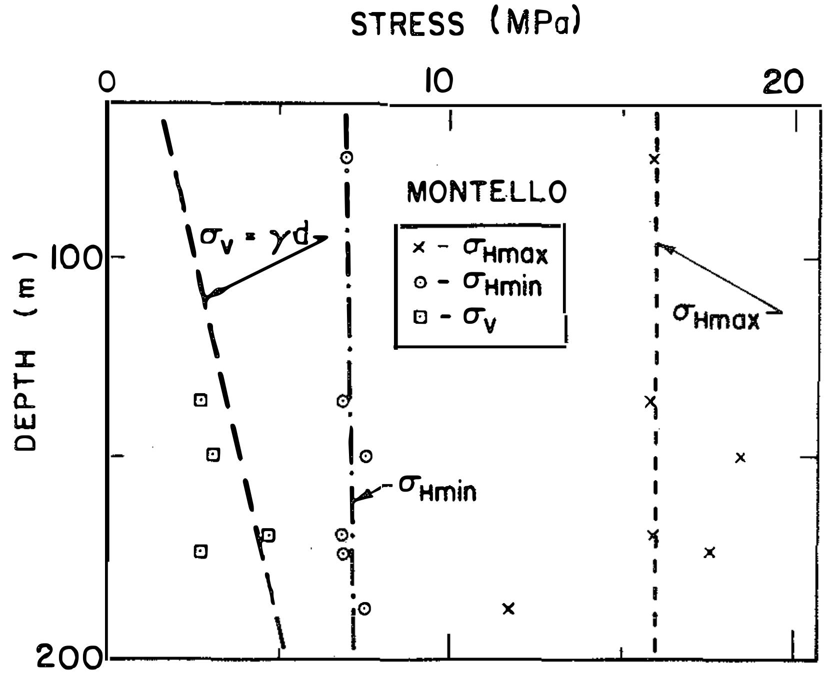

Figure 5. Variation of the three principal stresses with depth (75-200 m) in the Montello granite.

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 σ_{Hmax} is oriented at N.60°E. ± 15° (Figure 6). With respect to

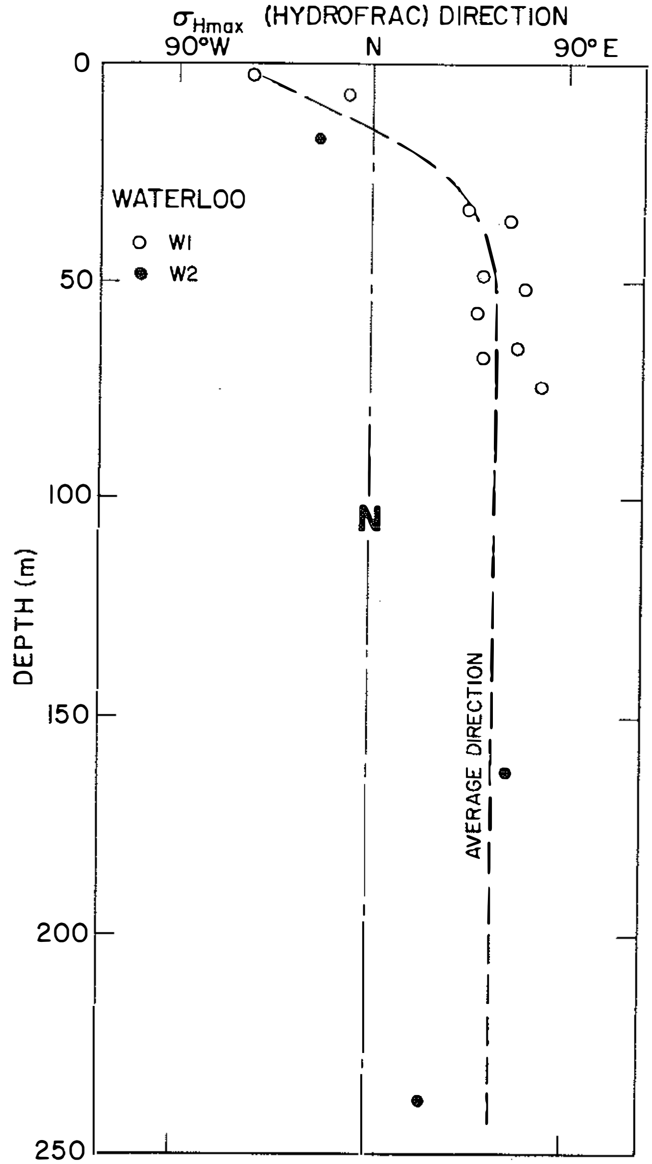

Figure 6. Variation of maximum horizontal stress direction with depth (0 - 250 m) in the Waterloo quartzite.

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 σ_{Hmin} = 5.5 + 0.008 d and σ_{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 σ_V = 0.026 d. For example, at a depth of 200 m the principal stresses are: σ_V = 5.2 MPa, σ_{Hmin} = 7.1 MPa at N.30°W. and σ_{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.

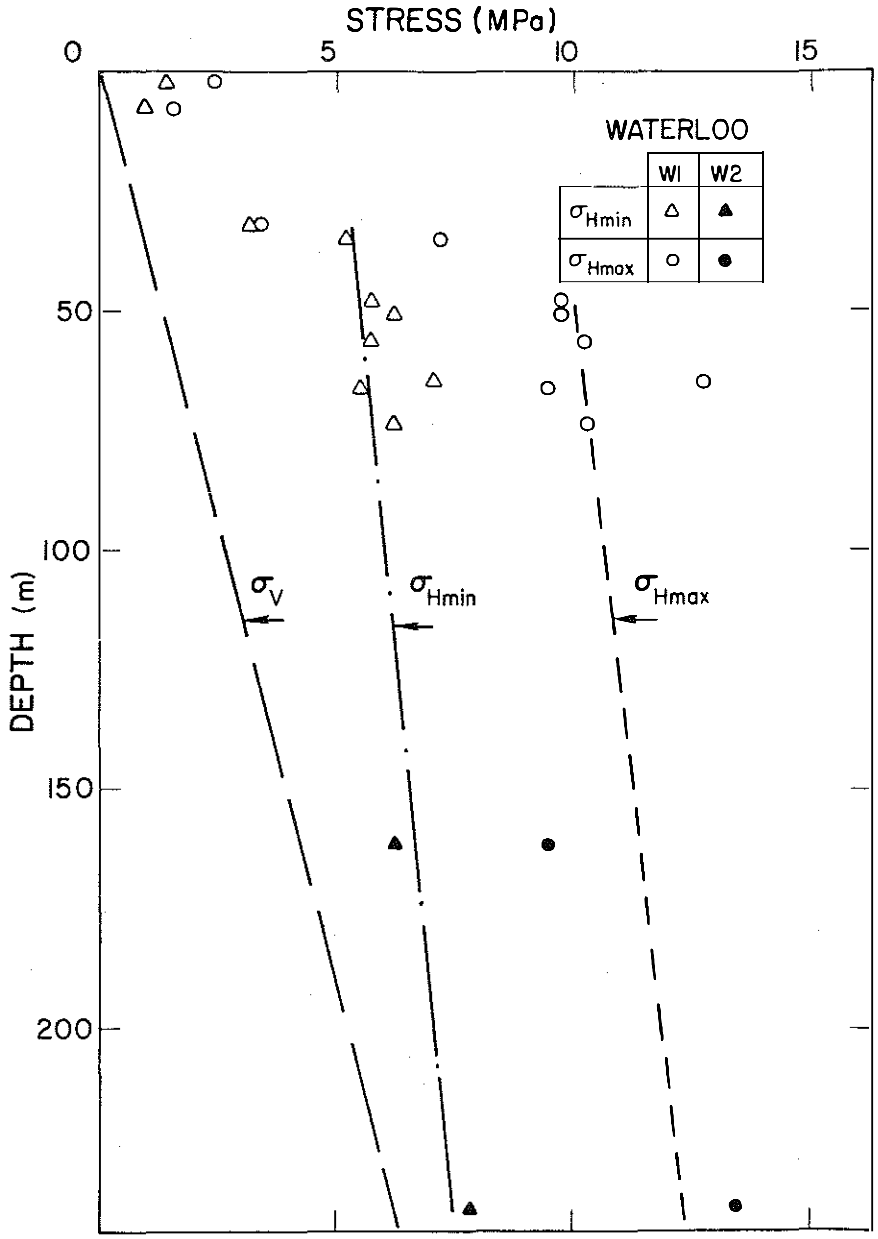

Figure 7. Variation of the three principal stresses with depth (0.250 m) in the Waterloo quartzite.

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". Table 3 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 x10^4MPa	E_T x10^4MPa	E_D x10^4MPa	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.

<u>Waterloo Quartzite Anisotropy</u>

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 8.5×10^4 MPa (at 30°) and the minimum of 7.5×10^4 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.

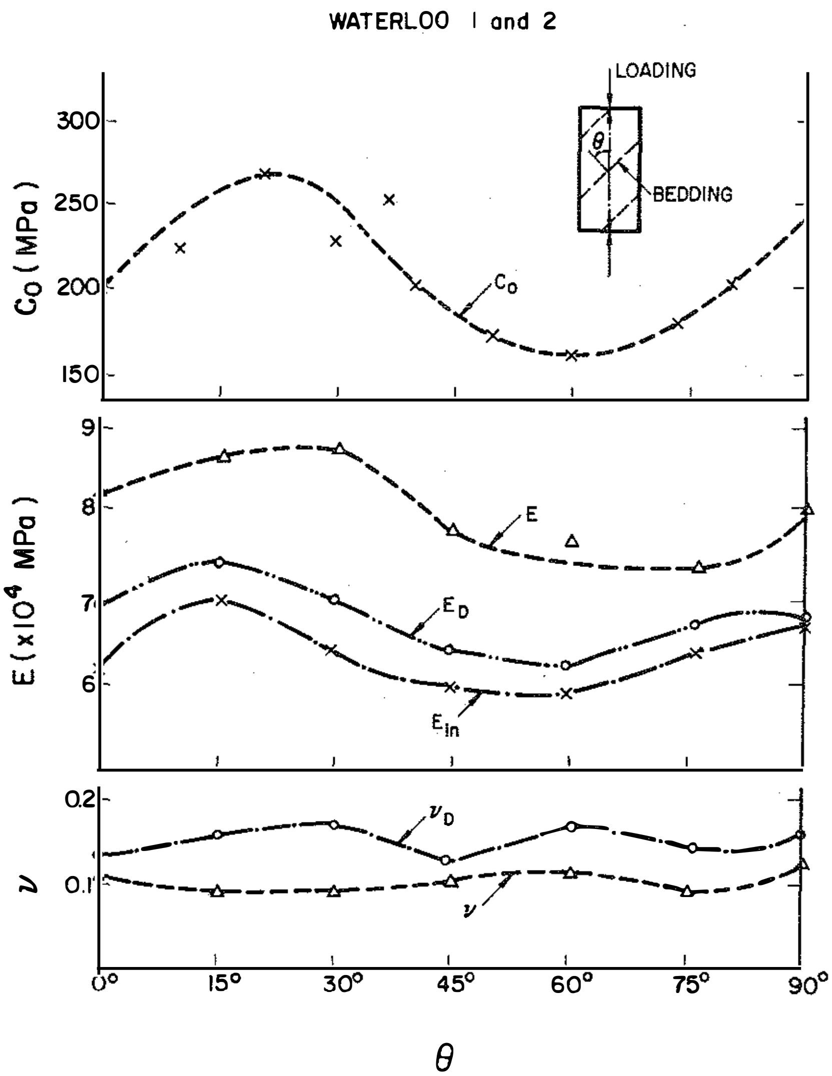

Figure 8. Variation of the uniaxial compressive strength (C_O), the average Young's modulus (E) and the Poisson's ratio ( ) with the angle - Waterloo quartzite (E_D and D are the dynamic values obtained from the measured compressional and shear velocities, Ein is the initial Young's modulus at the onset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

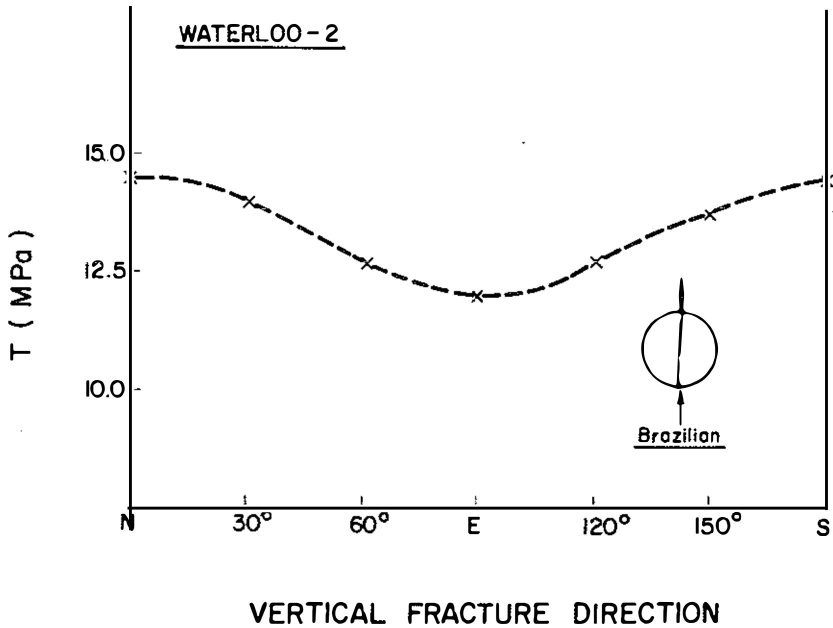

Figure 9. Variation of the Brazilian test tensile strength (T) with the direction of loading in samples of vertical core from hole W2 - Waterloo quartzite.

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.

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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.

Wisconsin Superconducting Energy Storage Project, 1977, Annual report, Engineering Experiment Station, University of Wisconsin-Madison.

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