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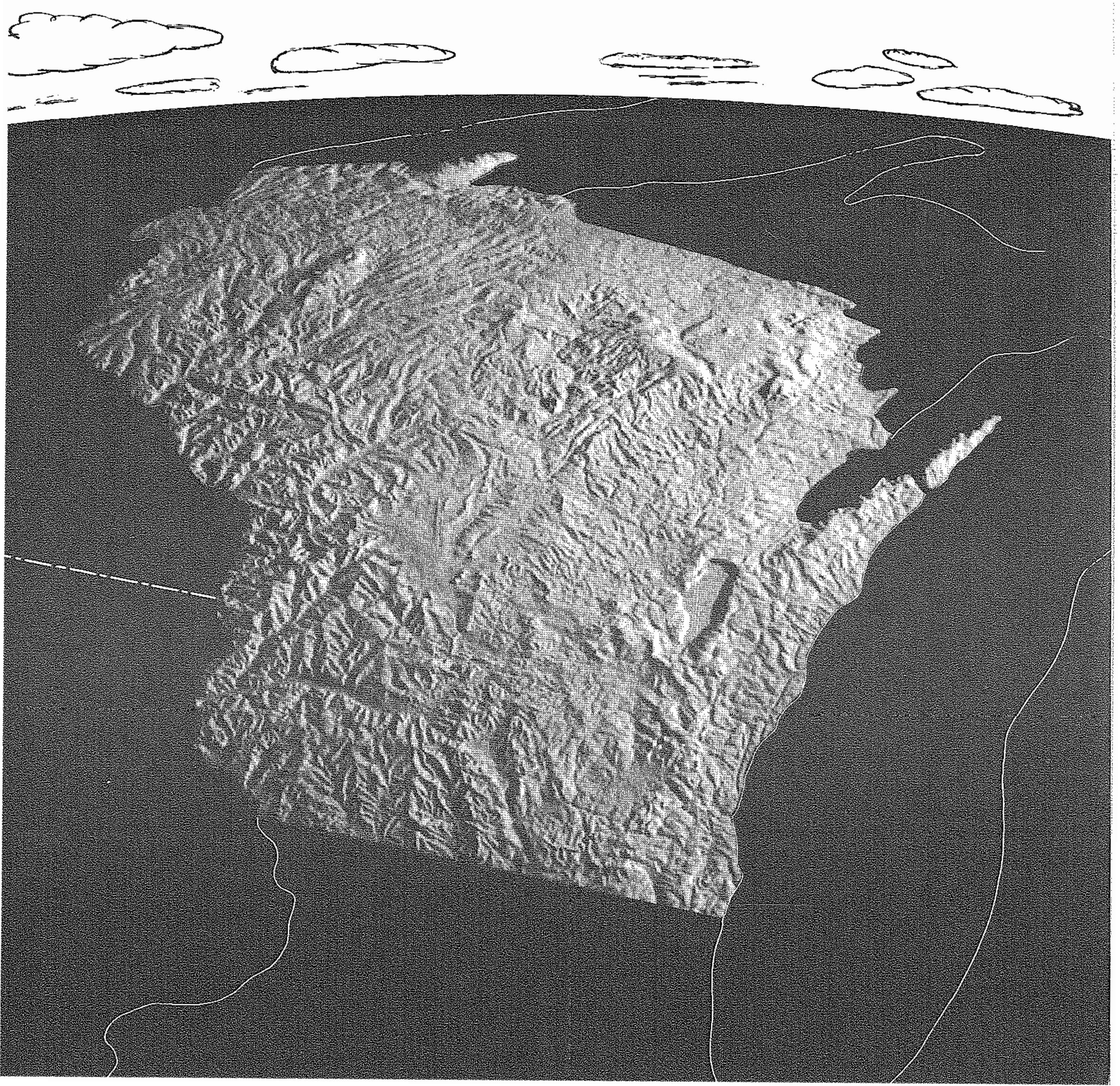

Cover: An oblique photograph of a plastic raised relief map of Wisconsin by Hans J. Stolle a graduate student in the Geography Department, University of Wisconsin - Madison.

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SOME ASPECTS OF THE PETROLOGIC AND TECTONIC HISTORY OF THE PRECAMBRIAN ROCKS OF WATERLOO, WISCONSIN

by

C.A. Geiger, C.V. Guidotti, and W.L. Petro

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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 copy of the paper, and the Geological and Natural History Survey will publish the paper as funds permit, distribute copies at 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.

The three papers in this issue include hydrogeologic evaluation, mineral resource evaluations, and metamorphic petrography and its relation to regional geologic history. D.A. Hackbarth documents fluctuations of semi-diurnal and diurnal periods in an observation water well near Peshtigo. Statistical evaluation of the data suggests that tidal effects are the cause for the variations. Victor F. Hollister and M.L. Cummings report on the rocks encountered in a mineral exploration program in Marinette County. This exploration did not encounter significant metallic mineralization, however the descriptions of the encountered units permit an increased understanding both of the lithology in the Proterozoic volcanic belt in Wisconsin, and the evolution of the hydrothermal sulfide system. C.A. Geiger, C.V. Guidotti and W.L. Petro report on the petrography of quartzites near Waterloo. Petrographic observation permits them to infer a sequence of metamorphic and structural events in the interval 1,760 to 1,630 m.y.

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

Wisconsin Geological and Natural History Survey

WATER-LEVEL FLUCTUATIONS DUE TO EARTH TIDES AT PESHTIGO, WISCONSIN

by

D. A. Hackbarth[1]

ABSTRACT

Water levels in an observation well near Peshtigo, Wisconsin, exhibit 3 cm fluctuations having semi-diurnal and diurnal periods. Fourier series analysis of tidal-gravity corrections and water-level fluctuations reveal two diurnal and two semi-diurnal waves with periods corresponding to established principle tidal waves. As the tidal-gravity correction increases (total gravity decreases) the water level in the well declines due to an expansion in pore volume caused by the tidal bulge of the solid earth.

The well is artesian and is completed in rocks of early Paleozoic age which are overlain by Pleistocene and Recent sediments in the Peshtigo River valley.

INTRODUCTION

Water levels in an observation well located in northeastern Wisconsin (approximately 45° north latitude and 87° 44' west longitude), about 2 km south of the city of Peshtigo, (Fig. 1), show regular fluctuations having an apparent period of about 25 hours and an amplitude up to 3 cm (Fig. 2). It was suspected that these fluctuations were caused by earth tides, therefore an analysis of fluctuations in water level, tidal gravity-corrections and barometric pressure was conducted. Similar comparisons have been made by Melchior (1978) for wells located elsewhere.

Water levels in two wells in Wisconsin, at Milwaukee and Richland Center, have been noted (Melchior 1966) to respond to fluctuations in tidal gravity. The well in Milwaukee is completed in Niagara Dolomite while the well at Richland Center terminates in rocks of Precambrian age. The amplitude of the water-level fluctuations was 2 to 3 cm, similar to those observed in the Peshtigo well. Melchior's (1966) note is the only published information on water-level fluctuations caused by changes in tidal gravity in Wisconsin.

The absolute gravity value at any point on the earth varies continuously as a result of the changing relative positions of the earth, sun, and moon. Time variations of absolute gravity are known as tidal-gravity fluctuations,

[1]Department of Geology, Northern Illinois University, DeKalb, Illinois; Now at Stanley Association of Engineering, Ltd., Edmonton, Alberta.

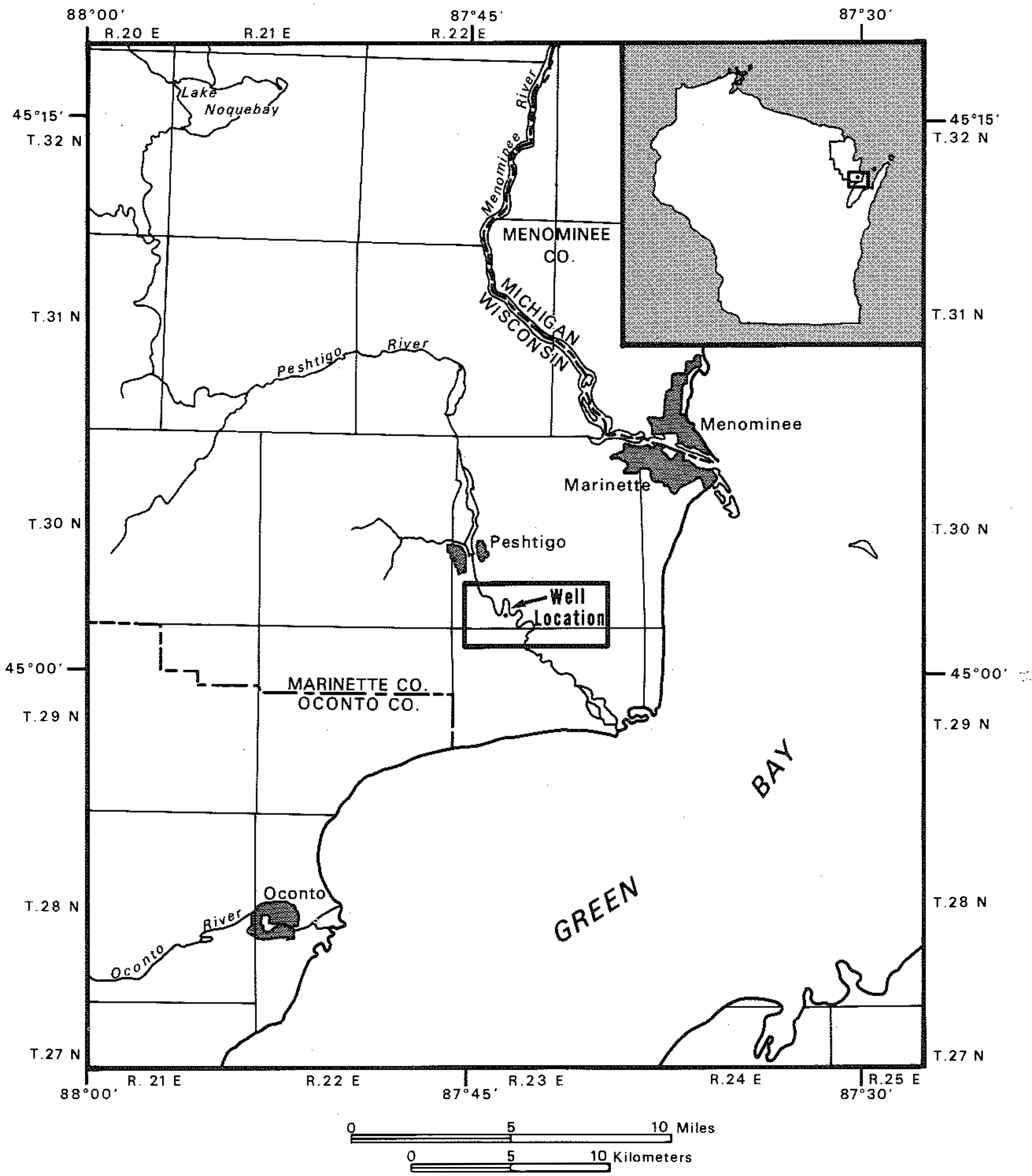

Figure 1. Location of Peshtigo Well, Mt-33.

whereas the up and down motion of the solid earth, in response to changes in total gravity, is a phenomenon known as earth tides. Tidal-gravity corrections are a time-sequence of positive and negative values which must be subtracted from absolute gravity values to give a constant gravitational acceleration at the point of interest. Expressed mathematically, for any instant in time, gravity minus the tidal-gravity correction equals a constant.

The relationship of water levels and the tidal-gravity correction is shown in Figure 3. As the tidal-gravity correction increases (absolute gravity decreases), the water level in the well falls. This behavior was noted by George and Romberg (1951) and Melchior (1966) and was attributed to dilation of the aquifer as the earth's crust bulges with decreasing gravity. When the tidal-gravity correction decreases (increasing gravity) the aquifer compresses slightly and water is forced into the well.

Earth tides have been recognized as the cause of periodic fluctuations of water level in wells by Robinson (1939), Richardson (1956), Stewart (1961), Marine (1975) and others (noted in Melchior, 1966) who made qualitative comparisons using lunar culminations. Tidal-gravity corrections can now be easily obtained from various sources, therefore there is no longer justification for analyzing water-level fluctuations caused by earth tides in such a qualitative manner. George and Romberg (1951) and Melchior (1966, 1978) demonstrated that the cause-and-effect relationship could be analyzed quantitatively by examining gravity fluctuations.

Two mechanisms besides earth tides could cause periodic fluctuations of water level in the Peshtigo well:

1. Ground-water pumpage (Peshtigo city wells are about 1 km away) and

2. Changes in total stress on the aquifer caused by;

a) Passing trains (railroad tracks are located 1.7 km away), and

b) Reservoir loading (a reservoir is located at Peshtigo for the purpose of generating electrical power).

In order to determine the apparent periodicity of water-level fluctuations in the Peshtigo well, a statistical analysis of measurements for the period of October 23, 1969 to November 26, 1969 was made. The period of the water-level fluctuations (Fig. 2 and 3) appears to be about 25 hours, which approximately coincides with the lunar day. The other mechanisms noted above are therefore removed from consideration by this analysis as possible causes of the water-level fluctuations because the trains, reservoir, or ground-water pumpage would be expected to have periods related to the 24-hour solar day.

WELL DATA

Elevation of the land surface at the well (Mt-33), drilled in 1968 during an environmental study for Badger Paper Mills, Peshtigo (Hackbarth, 1971), is about 181 m above mean sea level. The well is located in the flood plain of the Peshtigo River which flows in a broad, flat valley in this area.

The well is 153 m deep and has an 20-cm diameter casing to a depth of about 10 m, the remainder of the well is without casing. The open portion of the well is divided into three sections by rubber packers located at depths of 21 and 44 m and held in place by a 10 cm diameter pipe extending to the surface. Water levels thus can be monitored in the intervals 10 to 21 m, 21 to 44 m and 44 to 153 m. The only section of the well exhibiting the regular water-level fluctuations is that from 44 to 153 m. This portion of the well is completed in rocks of Cambrian and Ordovician age (Table 1). Regular daily fluctuations of water level were not observed in the two shallower segments.

The approximate elevation of hydraulic heads in the three segments of the well are; 181 m (10 to 21 m portion), 183 m (21 to 44 m portion), and 176 m (44 to 153 m portion). The water table is at an elevation of about 180 m at the well site which indicates that water is moving from the Sinnipee Group (Table 1) upward into the glacial drift and also downward into the underlying formations. The Peshtigo River is thus a discharge area for ground water at depths less than about 44 m.

Observations made during the drilling of the well indicate that the dolomite of the Prairie du Chien Group (Table 1) is dense, does not yield much water, and probably acts as an aquitard. The Jordan and St. Lawrence formations, although not actually tested, appeared to be capable of yielding about 10 L/s during air-rotary drilling. These two units probably represent the aquifer which experiences the fluctuations of water level measured in well.

Table 1. Stratigraphic succession and lithology

SYSTEM UNIT	Depth (m) FROM	 TO	LITHOLOGY
QUARTENARY			
Pleistocene	0	8.5	Sand
ORDOVICIAN			
Sinnippee Group	8.5	41.1	Dolomite
Prairie du Chien Group	41.1	102.1	Dolomite
CAMBRIAN			
Jordan Formation	102.1	117.7	Sandstone
St. Lawrence Formation	117.7	147.8	Dolomite
Tunnel City Group	147.8	153+	Sandstone

Stratigraphic interpretation by Wisconsin Geological and Natural History Survey - Log No. Mt-33.

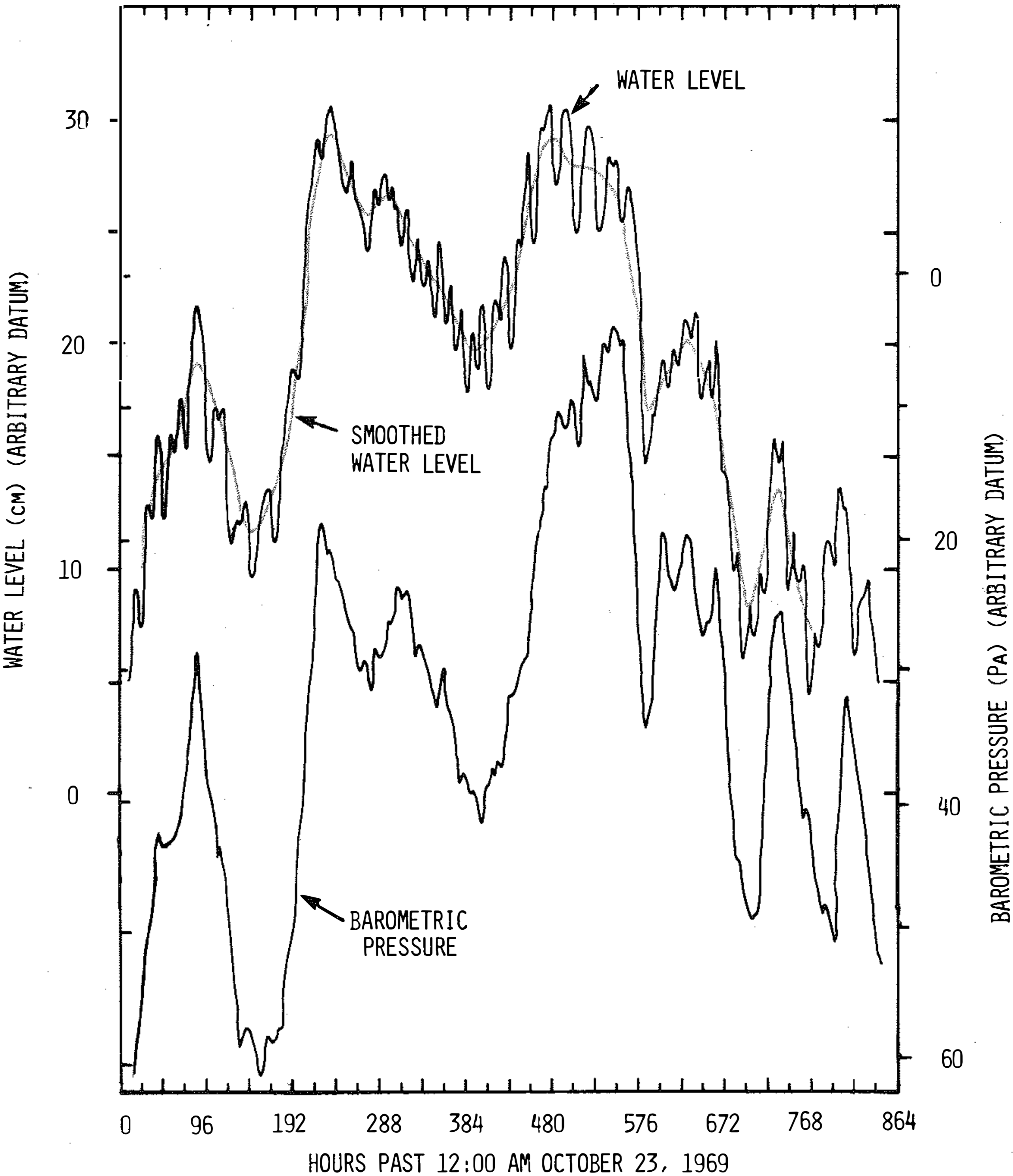

Figure 2. Water level and barometric pressure fluctuations in well Mt-33 on October 23, 1969.

DATA ANALYSIS

The water-level hydrograph of the well (Mt-33) was digitized at one-hour increments for the period from October 23 to November 26, 1969. Barometric pressures were obtained from a nearby recorder and were also digitized at one-hour intervals. Hourly tidal-gravity corrections at the well were calculated from tables given by Service Hydrographic de la Marine (1969).

Comparison of the graphs (Fig. 2) of barometric pressure (note that it is inverted) and water levels shows an abvious relationship. Water level appears to be responding to barometric pressure changes, at least to those with a period of one day or more, with the expected inverse relationship. An average barometric efficiency of 88 percent is indicated from analysis of nine of the major fluctuations shown on Figure 2. Autocorrelation (Davis, 1973) of the barometric record indicates however, that regular periodic fluctuations of atmospheric pressure did not occur. Therefore, variations in barometric pressure, although causing non-periodic changes of water level, were not contributing to the regular daily fluctuations and were eliminated as a possible cause of those fluctuations.

Further analysis of the digitized water-level data required the removal of variations other than those suspected to be caused by fluctuations in tidal gravity (for instance, the long-period barometric responses noted above). This was accomplished in two steps:

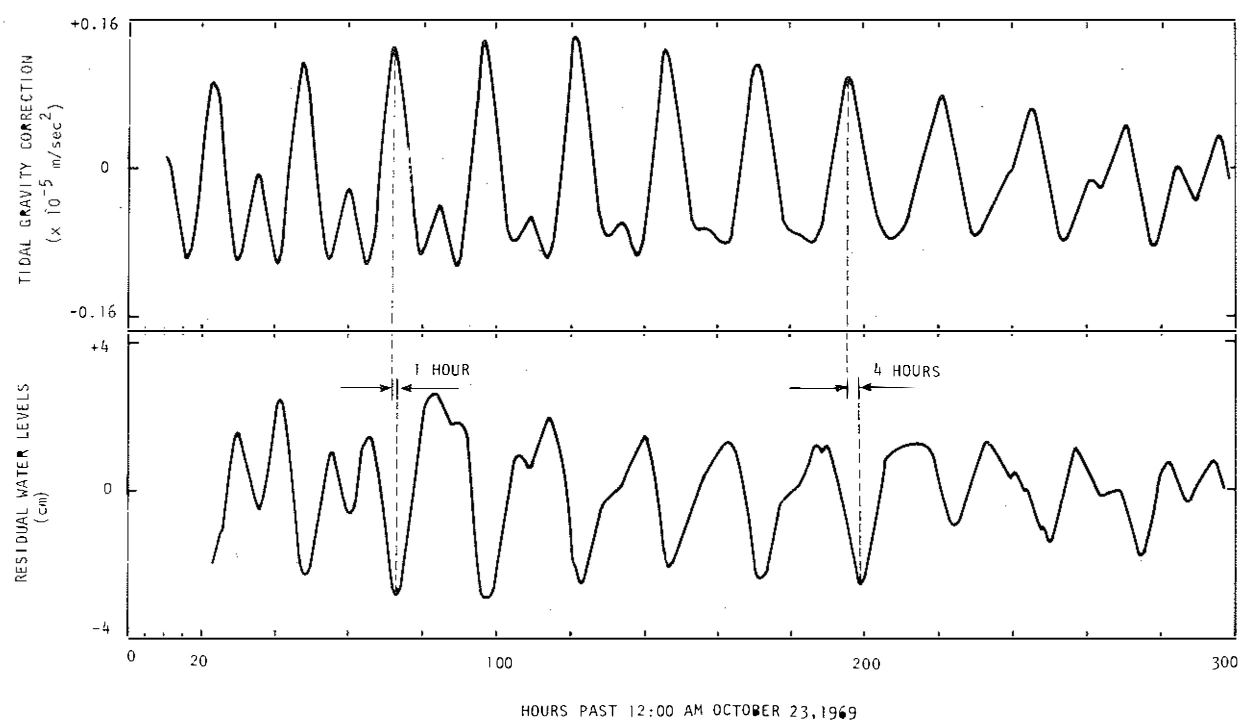

Figure 3. Tidal-gravity correction and residual water levels.

1. A new set of smoothed hourly water-level elevations was calculated by a 25-hour moving average technique. The moving average utilized information for 12 hours before and after each hourly data point. The smoothed curve is shown on Figure 2. The selection of 25 hours for a moving average was to eliminate fluctuations having semi-diurnal and diurnal periods. On the other hand, a longer interval for the moving average might tend to smooth out the broad fluctuations caused by barometric pressure changes (Fig. 2) and this was also undesirable.

2. The above set of smoothed data points was subtracted from the original set of water-level elevations to produce a new set of residual water levels (Fig. 3). The fact that the residual water levels are stationary (Davis, 1973) indicates that the above procedure was appropriate. Had the procedure been incorrect the residual water levels would not have plotted with such symmetry about the axis of zero fluctuation. Figure 3 presents only a 300-hour segment of the 817-hour period which was actually analyzed.

Fluctuations of the residual water-levels have an amplitude up to 3 cm and their correlation, in terms of time and amplitude, with tidal gravity corrections is apparent (Fig. 3). This set of residual water-levels and tidal-gravity corrections was further analyzed using a Fourier-series technique (Davis, 1973).

The Fourier-series technique confirms that the major wave forms of the residual water levels conform with those of the tidal-gravity correction (Table 2) and that both of these correspond, considering the length of time analyzed and the hourly increments of the two data series, with the periods of the principle tidal waves as noted by Melchior (1978). There is some minor uncertainty about the correspondence of the diurnal M_1 wave. However, this does not detract from the conclusion that the water-level fluctuations must be caused by earth tides.

The Fourier series allows calculation of the amplitude of any wave from the power assigned to it at a specified frequency (Davis, 1973). The ratio of the amplitudes of the four tidal-gravity waves should be the same as the ratios of the amplitudes of the corresponding water-level waves to prove a cause-and-effect relationship (Melchior, 1966). The corresponding wave-amplitude ratios are essentially equal (Table 2) which further confirms that the fluctuations of tidal gravity are causing the fluctuations of water levels. The wave-amplitude ratios for the diurnal (b) to semi-diurnal (c) water-level waves are very similar to values shown by Melchior (1978) for locations of similar latitude elsewhere.

Table 2. Summary of Fourier-series analysis of residual water levels and tidal-gravity corrections.

Wave*	Period**			Amplitude	
	Residual Water level, ± error (hours)	Tidal Gravity, ± error (hours)	Principle Tidal Waves (hours) (1)	Residual Water Level (cm)	Tidal Gravity ($\times 10^{-5}$ m/sec^2)
a. K_1, P_1 waves	24.4 ± 1.1	23.7 ± 0.7	23.93&24.07	0.40	0.029
b. O_1 wave	26.8 ± 0.9	26.0 ± 0.8	25.82	0.38	0.021
c. M_2, N_2 waves	12.8 ± 0.2	12.4 ± 0.3	12.42&12.66	0.38	0.023
d. S_2 wave	12.2 ± 0.2	12.0 ± 0.3	12.00	0.14	0.008

WAVE-AMPLITUDE RATIOS

	Residual Water Level	Tidal-Gravity Correction
a/b	1.1	1.3
a/c	1.1	1.3
a/d	2.9	3.6
b/c	1.0	0.9
b/d	2.7	2.6
c/d	2.7	2.9

* Symbols refer to diurnal (subscript 1) and semi-diurnal (subscript 2) tidal waves of Melchior (1978).

** (2) Length of analysis is October 23 to November 26, 1969 (831 hours).

Theoretically, the response of the water level in the well to changes in gravity should be instantaneous (Robinson and Bell, 1971), however, a phase shift occurs between the tidal-gravity correction and residual water-level waves. The water level exhibits a phase shift (Fig. 3) which appears to vary from zero to four hours between the maxima or minima of the tidal-gravity correction and the minima or maxima of the residual water-level fluctuation. The apparent lag is probably due to errors in digitization of the water-level hydrographs. Splicing of recorder charts was necessary which may account for the increase in phase shift with increasing time.

SUMMARY

1. The well Mt-33 at Peshtigo has the following physical characteristics:

   a) the well is completed in Cambrian and Ordovician sandstones and dolomites,

   b) the Prairie du Chien Dolomite, a rock unit of low hydraulic conductivity, overlies the zone contributing water to the well,

   c) hydraulic head is 36 m above the top of the aquifer,

   d) the well is adjacent to the Peshtigo River where ground-water discharge occurs from depths less than about 44 m, and

   e) diurnal and semi-diurnal fluctuations of water level with an amplitude up to 3 cm are observed.

2. Fourier series analysis of residual water levels and tidal-gravity corrections revealed two diurnal and two semi-diurnal waves which correspond to principal tidal waves identified by Melchior (1978). This is strong evidence that the fluctuations of water level are caused by earth tides.

3. The fact that wave-amplitude ratios of corresponding tidal-gravity corrections and water-level fluctuations are approximately equal confirms a cause-and-effect relationship. Water levels vary inversely with tidal-gravity corrections.

ACKNOWLEDGMENTS

Data for the Peshtigo well were obtained through the support of the Wisconsin Department of Natural Resources. The geological log of the Peshtigo well was supplied by the Wisconsin Geological and Natural History Survey.

The author would like to thank Dr. L.D. McGinnis and Dr. C.P. Ervin of Northern Illinois University, Dr. F.W. Schwartz of the University of Alberta, and Mr. G. Gabert of the Alberta Research Council for their comments on the manuscript.

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A SUMMARY OF THE DUVAL MASSIVE SULFIDE DEPOSIT, MARINETTE COUNTY, WISCONSIN

by

Victor F. Hollister[1] and M.L. Cummings[2]

ABSTRACT

The Duval Deposit in west-central Marinette County, Wisconsin, is a conformable, pyrrhotite-rich, massive sulfide lens that contains only trace amounts of base and precious metals. It occurs in an amphibolite facies submarine volcanic sequence that was characterized by calcalkaline basic flows, tuffs, iron formation and carbonaceous clastic sediments. The stratigraphy near the sulfide unit consists, from bottom to top, of: 1) interlayered massive basalt flows, basic tuffs and thin sulfidic carbonate iron formation, 2) a sulfidic iron formation that is overlain by the massive sulfide, and 3) graphitic mudstones and siltstones. The massive sulfides separate an upper marine clastic sedimentary sequence from a lower submarine volcanic and iron formation sequence.

Lack of unambiguous evidence for a footwall feeder conduit and absence of significant metal zoning are compatible with deposition of the graphitic sulfide mass in a distal or sedimentary basin rather than proximal to a volcanic center. The Eh-pH-f_{S_2} conditions did not favor precipitation of base metal sulfides; consequently copper and zinc sulfides are present only in trace amounts.

INTRODUCTION

The Duval Corporation conducted geological, geophysical and pilot exploratory drilling programs from 1971 through 1974 on an unexposed conformable massive sulfide body at 88° 14' W, 45° 35' N (sec. 2 and 3, T.35N., R. 18E. and Sec. 28, T.36N., R. 18E) in west-central Marinette County, Wisconsin. The deposit, which contains mainly iron sulfide, is referred to as the Duval Deposit by the mining industry and was discovered by airborne geophysical methods. The massive sulfide layer occurs in the Precambrian rocks of northeastern Wisconsin in a layer up to 30 m thick. Drilling suggests the deposit contains on the order of 10 million tons of sulfide-rich material that could supply 3 million tons of recoverable sulfur. At present, however, neither metallic nor nonmetallic reserves have been proven. Pertinent technical data, including geologic, geochemical, drill data, and core, for the deposit were given to the Wisconsin Geological and Natural History Survey and the University of Wisconsin (Cummings, 1978) and are available to the public.

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[1]6071 Madrona Crescent, Richmond, B.C., Canada V7C 2T3

[2]Department of Earth Sciences, Portland State University, Portland, Oregon 97207

The Duval cores are part of the Survey collection of drill cores which are available for public inspection at the core repository in Milwaukee during the first full work week of each month. For additional information on the cores collection, or on the core repository, please contact the Exploration records Specialist at the Wisconsin Geological and Natural History Survey (608/262-1705).

The Duval sulfide deposit differs from other known large massive sulfide deposits in Wisconsin. It is nearly devoid of base and precious metals; it separates a dominantly basic submarine volcanic and iron formation footwall assemblage from a hangingwall marine clastic sequence; and it occurs with sulfidic carbonate iron formation. This paper briefly describes the Duval deposit and considers why the Duval massive sulfide, unlike the Kennecott (May, 1977), Noranda (Mudrey, 1979) and Exxon (Schmidt and others, 1978) discoveries, is barren of significant copper, zinc and lead. Careful documentation of the geology of sub-economic deposits and comparison to economic deposits may provide valuable clues to differences in the systems that formed the deposits and provide useful information to guide exploration for economic deposits.

The data on which the following sections are based can be found in Cummings (1978).

GEOLOGIC SETTING

The Duval massive sulfide deposit occurs in the Lower Proterozoic volcanic rocks of west-central Marinette County, Wisconsin (Fig. 1). The volcanic rocks have been included in the Quinnesec Formation (Cummings, 1978). The Quinnesec Formation is a name generally applied to those mafic volcanic rocks of Dickinson County, Michigan and adjoining northeastern Wisconsin. Recent work (Cummings, 1980) on the petrochemistry of the volcanic rocks indicates that they are dissimilar to the Quinnesec Formation as sampled in the area defined as Quinnesec Formation by Jenkins (1973) and chemically analyzed by Cudzilo (1978). In the vicinity of the Duval Deposit, the volcanics are composed of basic submarine volcanic, volcaniclastic and sedimentary rocks. Although Banks and Rebello (1969) reported U-Pb ages on zircon from a rhyolite east of the massive sulfide deposit in what was believed to be the Quinnesec Formation, the age of the mafic rocks associated with the deposit remains unknown. The volcanics are bounded by 1860 to 1890 m.y. old granitic plutons (Banks and Cain, 1979, Van Schmus and others, 1975). Cummings (1978) concluded from mineralogy that metamorphism of the deposit occurred at amphibolite grade and that peak temperature of 540° C and maximum pressure of 3.5 kb was reached during metamorphism.

The volcanic sequence in west-central Marinette County consists of massive and fragmental basalt, andesite, dacite and rhyolite flows, tuffs, volcaniclastic, clastic and chemical sedimentary rocks. The flow units represent an orogenic calcalkaline suite. The massive sulfide deposit occurs in sedimentary units that appear to have been deposited some distance from a major volcanic center in a sedimentary basin characterized by chemical sedimentation, fine-grained graphitic clastic sediments and quiet, probably deep water.

The stratigraphic relations of the sulfide unit has been defined from drill core since the unit does not crop out. Sparse top indicators in core samples suggest that the units are folded about an anticlinal axis that plunges gently to the southeast (Fig. 2). The limbs of the anticline are steeply dipping. Since the drill holes were drilled to the south on the north limb and

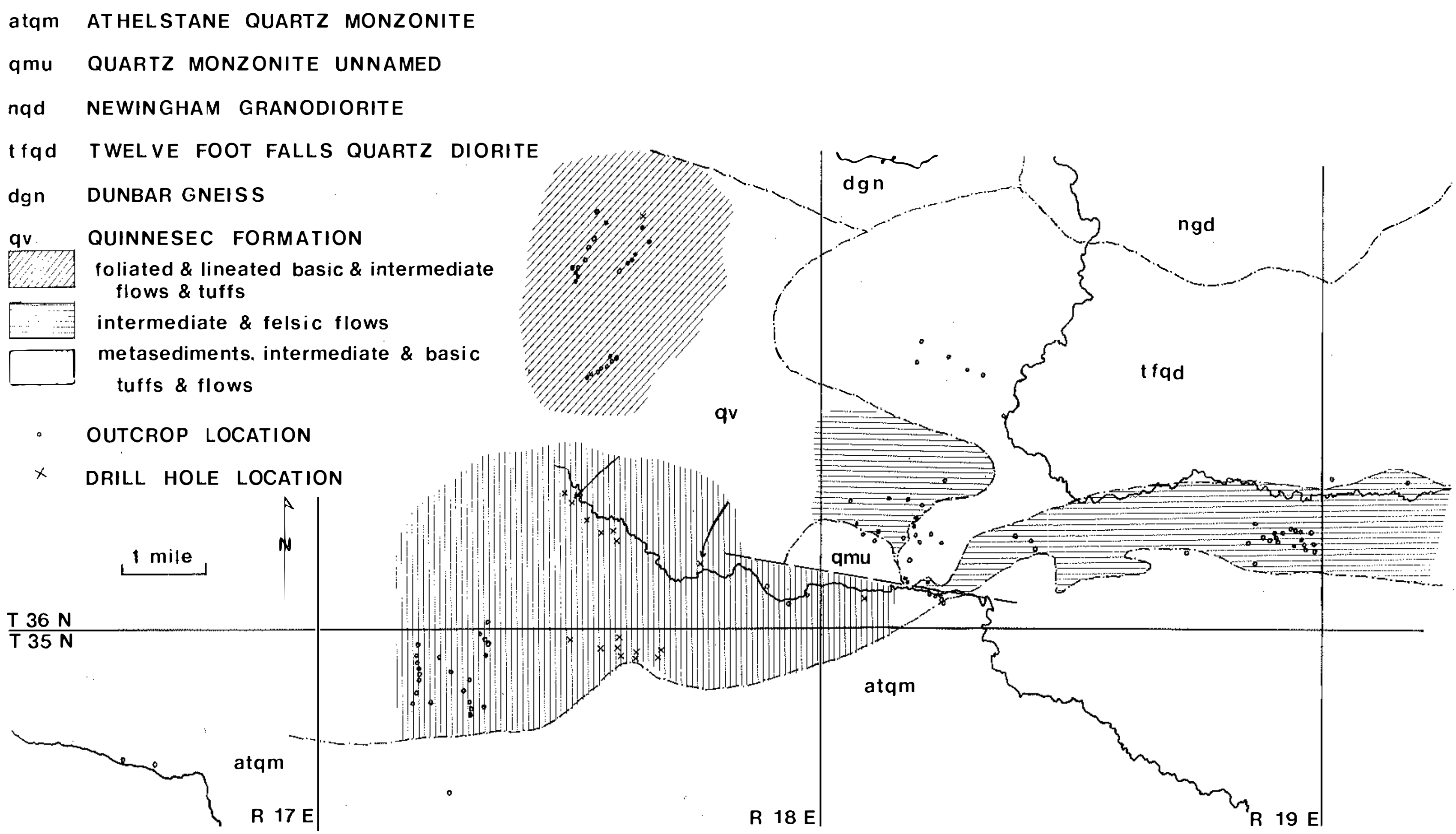

Figure 1. Generalized geologic map of west-central Marinette County, Wisconsin.

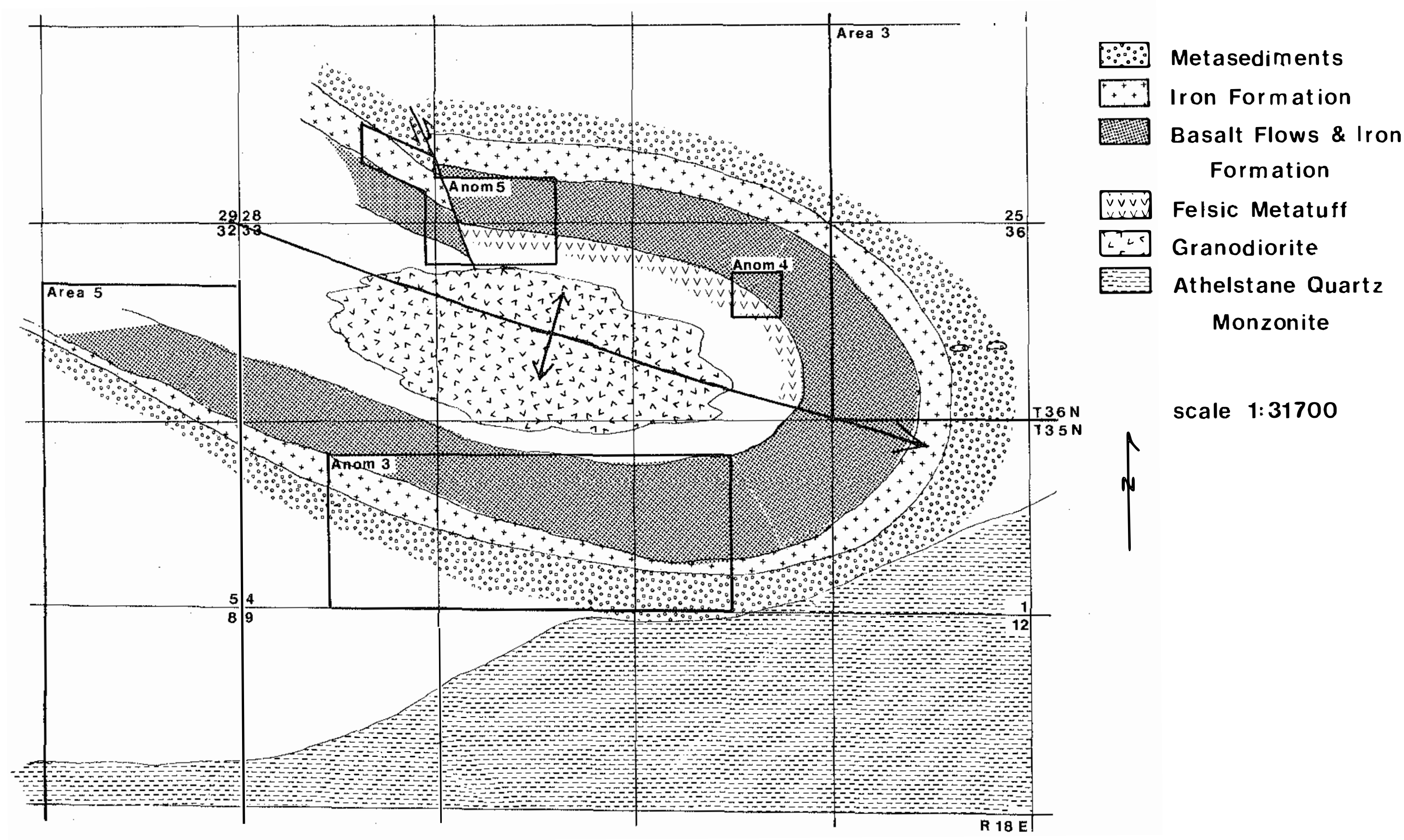

Figure 2. Geologic interpretation of an anticline in the area of the Duval deposit.

to the north on the south limb of the anticline, the rocks at the bottom of the holes are believed to be the oldest units. The stratigraphy associated with the Duval massive sulfide includes approximately 220 m of massive basalt flows, interflow basic tuffs and thin layers of sulfidic carbonate iron formation. The basalt flow unit is overlain by a sulfidic carbonate iron formation lens that varies in thickness from 10 to 40 m. Massive to semi-massive graphitic sulfide in a bed up to 30 m thick conformably overlies the iron formation and in turn is conformably overlain by graphitic mudstones and well-bedded siltstones. Sulfide minerals comprise less than 5 percent of the upper sedimentary unit.

DESCRIPTION OF ROCK UNITS

Basalt Flow Unit

Basalt flows are the main rock type in the unit. The flows are from 1- to 60-m thick and are massive. The textural relations between hornblende and plagioclase preserves a relict sub-ophitic texture in most flows. Each flow is generally overlain by faintly bedded basic tuff. The tuffs commonly contain beds up to 2-mm thick that are greater than 60 percent epidote. Besides epidote, the mineralogy of the tuffs includes actinolitic hornblende, chlorite and minor plagioclase. The mineralogy suggests basic ash contaminated by carbonate. The basic tuffs grade stratigraphically into sulfidic carbonate iron formation. Iron formation lenses can be as much as 1-m thick and contain up to 20 percent sulfide. Pyrrhotite, with traces of chalcopyrite, pyrite and sphalerite are disseminated in some amphibole-rich beds.

Iron Formation Unit

The iron formation lenses in the volcanic sequence are believed to represent metamorphosed carbonate-chert iron formation. Under metamorphic conditions of the amphibolite facies, the carbonate has apparently reacted with silica to produce interlayered quartz and iron-amphibole beds. The iron amphiboles, the main phases in the iron formation, are overwhelmingly grunerite with minor to trace amounts of ferro-actinolite and ferro-hornblende. The carbonate, present in trace amounts, is calcite. Garnet and stilpnomelane are locally present. The composition of the iron-rich beds is basically represented by the composition of the grunerite which ranges from 31 to 45 weight percent FeO (Cummings, 1978). Where magnetite is present the weight percent of FeO in grunerite is lower and cummingtonite may occur as the main amphibole (amphibole classifications are according to the Subcommittee on Amphiboles, IMA, Leake, 1978).

The iron formation unit was divided by Cummings (1978) into an upper and lower member. The lower member is characterized by pyrrhotite beds to 2-mm thick, but sparse sulfide beds may reach 10 cm in thickness. Traces of chalcopyrite and sphalerite are megascopically visible in some beds. The upper member contains stilpnomelane with grunerite, and garnet-graphite-quartz beds become common. Sulfide minerals are finely disseminated in iron silicate beds except in the upper part of the member where sulfides are interbedded with quartz beds. The sulfide beds become more abundant toward the top of the unit. Magnetite is most abundant (greater than 10 percent) in the upper part of the lower member and lower part of the upper member. Ilmenite, determined by microprobe analyses, is the oxide phase in some beds.

Massive Sulfide Unit

The percentage of sulfide in the upper part of the iron formation unit increases and becomes semi-massive (10- to 40-percent sulfide). The sulfides are well bedded, however in the main sulfide zone the sulfide forms a matrix between fragments of polycrystalline quartz and graphitic lithic sediments. In the main zone the sulfide is semi-massive to massive. The main sulfide mineral is pyrrhotite; pyrite is rare and sphalerite and chalcopyrite occur in trace amounts. Zoning of metal values has not been noted in the deposit and lateral persistence of internal textures, structures or composition have not been shown. Drill intercepts indicate thicknesses from 3 m to 20 m for the fragmental unit along a strike length of at least 1300 m. The fragmental unit is considered a sulfur resource that contains roughly 10 million tons of sulfide ore. If the semi-massive sulfide layers in the iron formation are included in the resource estimate the tonnage approaches 40 million tons.

Magnesium-rich silicate assemblages underlie the sulfide unit and are texturally and structurally similar to the sulfide-rich upper iron formation member. Such magnesium-rich silicates are noted at least 5 m below the base of the main sulfide unit but may locally be absent. Bedding structures in the materials are similar to those in iron formation even though the mineralogy is tremolite and muscovite rather than iron silicates. Fragmental textures in an apparent basic crystal tuff are preserved in an assemblage containing anthophyllite and Mg-Fe chlorite.

Mudstone and Siltstone Unit

Well-bedded clastic sediments overlie the massive sulfide unit. The sediments immediately above the sulfide unit are highly graphitic and fine grained. Folds in the unit are believed to represent soft-sediment deformation features. The amount of graphite decreases upward as the grain size becomes coarser until the unit is a graphitic, well-bedded siltstone. Pyrrhotite and minor pyrite form thin beds in the mudstone and siltstone and range to 5 percent as disseminated grains in thin hornblende-epidote-plagioclase beds that may represent basic tuffs.

DISCUSSION

The Duval Deposit appears to have been deposited in a chemically reducing, sedimentary basin that was not in the immediate vicinity of a volcanic center. Plimer (1978) suggested several characteristics that distinguish stratabound deposits formed at varying distances from volcanic centers. The deposits formed near the center, called proximal deposits, occur in intermediate to acid explosive volcanic rocks in parts of the volcanic pile where the proportion of lavas and pyroclastic rocks to sediments is high. Alteration pipes, stringer sulfide zones and disseminated sulfides are common in the footwall of the proximal deposits. The deposits formed away from a center, or distal deposits, are found in areas where there is a high proportion of clastic and chemical sediments to pyroclastic rocks and lava flows. There is no clear spatial relation of the deposit to a footwall alteration pipe or stringer zone. In terms of the associated stratigraphy, the Duval Deposit is a distal deposit, however the origin of the Mg-rich zone beneath the sulfide unit is not clear and must be considered.

There are three possible origins for the magnesium-rich zone: 1) a metamorphosed dolomitic cherty tuff as protolith for the tremolite-bearing rocks. 2) a metamorphosed epigenetic feeder pipe that owes magnesium enrichment to metasomatism during sea floor hot spring activity, or 3) the effects of metamorphic reactions in the immediate vicinity of the sulfide-silicate unit contact. The available data do not allow a clear choice among the three possible origins.

The mineral assemblages of the zones contain high magnesium phases and are in marked compositional contrast to underlying iron formation. The Mg/(Mg + Fe) ratios for tremolite are 0.98 and are 0.90 for associated chlorite. The iron-bearing phases are sulfides and tourmaline has been noted in one assemblage. The anthophyllite-bearing assemblage is more iron-rich. The Mg/(Mg +Fe) ratio for anthophyllite is approximately 0.82 and 0.55 for associated chlorite. The proposed origin for the zone must be consistent with these facts.

The first proposed origin suggests a sedimentary protolith for the deposits. A siliceous dolomite mixed with volcanic ash or clays might be the parent material for the tremolite-bearing assemblages. The suggested protolith would indicate depositional change from siderite + chert to dolomite + chert to massive sulfide + chert upward in the stratigraphic sequence. Such associations of various carbonate phases and massive sulfide deposits have been noted in pyrrhotite and pyrrhotite + pyrite massive sulfide units recorded in Rhodesia where carbonate units from iron formation to limestones are closely associated with massive sulfide deposits (Anhaeusser and Ryan, 1976). Although a parent rock can be proposed, there are problems with the interpretation. The replacement textures in the basic tuff bed that now contains anthophyllite and chlorite are not explained by the sedimentary model. Also the irregular thickness of the magnesium-rich zone does not seem consistent with a sedimentary model. The zones may be absent in some holes and at least 5-m thick in others, suggesting possible discordant relations to the enclosing stratigraphy.

The replacement textures in the basic tuffs and possible replacement of iron formation by the tremolite assemblages suggest alteration of sediment by metasomatic activity. Plimer (1978) suggested that alteration associated with distal massive sulfide deposits should show slight increases in K_2O, FeO, MnO, TiO_2 and SiO_2 and slight decreases in Na_2O, CaO and MgO. The tremolite assemblages suggest MgO and CaO may have been added to the rock rather than subtracted. The composition and mineralogy of the assemblage does not appear consistent with the compositions and mineralogies of known alteration zones associated with massive sulfide deposits (Simmons, 1973; Gilmour, 1965; Spence and Rosen-Spence, 1975; Kelly, 1975; Walker and others, 1975; Roberts, 1975; Franklin and others, 1975).

The third possible origin, metamorphogenic processes, is suggested by the effects of sulfurization reactions or fluid phase reactions during metamorphism. This interpretation would indicate that the magnesium-rich bulk composition was established during metamorphism. A magnesium-rich silicate assemblage can be produced by sulfurization reactions at elevated temperatures (Bischoff and Dickson, 1975), however, the reactions should produce calcium-poor assemblages since calcium is enriched in the vapor phase. Also, if the magnesium-rich materials were produced by sulfurization reactions, then the sulfide minerals would probably not show a bedded pattern. The circulation of fluids during metamorphism has been suggested as a mechanism to produce alteration zones around the deposits at Ducktown, Tennessee (Abby and Yuma, 1977). In the model, trace sedimentary sulfide was remobilized during regional metamorphism and the sulfide was deposited by hydrothermal solutions in shear zones. The alteration zones around the ore bodies occurred late during the matamorphism as water continued to pass through the shear zones in which the deposits occur. There is neither evidence for sulfide deposition in shear zones nor alteration surrounding the Duval Deposit. The magnesium-rich assemblages are only in the footwall of the deposit.

Although the three proposed models for the origin of the magnesium-rich zones associated with the Duval Deposit can be supported by some data, the models either cannot explain all the features of the zones or are apparently contradicted by features in the zones.

The physical-chemical environment of sea water at the time of deposition is reflected in the chemical sediments that form. Eh, pH and f_{S_2} would affect either magnetite, magnetite-pyrrhotite or pyrrhotite deposition in the bed. The increasing proportion of pyrrhotite rather than magnetite upward in the iron formation suggests steadily increasing f_{S_2}, possibly the result of increased biological activity.

If the Eh, pH and f_{S_2} conditions remained close to the boundary for coprecipitation of pyrrhotite and magnetite, then there was a limited likelihood of chalcopyrite and sphalerite deposition (Large, 1977). The concentration of copper and zinc in seawater as the Duval Deposit was formed cannot be known, however, the presence of chalcopyrite and sphalerite in iron formation and massive sulfide, although not exceeding 0.5 percent irrespective of the percentage of sulfide in the rock, indicates the presence of metals during the depositional process. Thus, the lack of base metals in the iron formation and sulfide units may have been a result of non-deposition due to environmental conditions rather than a lack of base metals in seawater.

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SOME ASPECTS OF THE PETROLOGIC AND TECTONIC HISTORY OF THE PRECAMBRIAN ROCKS OF WATERLOO, WISCONSIN

by

C. A. Geiger[1,2]
C. V. Guidotti[1,3]
W. L. Petro[1]

ABSTRACT

Study of the highly aluminous pelitic schists interbedded with the Waterloo Quartzite of southern Wisconsin suggests at least two periods of deformation followed by two separate metamorphic events (M_1 and M_2). Both metamorphisms occurred in a static environment and although both probably took place under amphibolite facies conditions, M_1 probably represents somewhat higher temperature conditions than M_2. Arguments are presented which suggest that M_1 occurred at P_{H_2O} < 3.8kb and T between 350°C and 550°C.

M_1 and M_2 clearly represent post-Penokean metamorphic events which may have occurred on a regional scale throughout much of southern Wisconsin. An age of near 1,630 m.y. seems most reasonable for these metamorphic events.

INTRODUCTION

The Waterloo Quartzite crops out about 35 kilometers northeast of Madison near the town of Waterloo (Fig. 1). These outcrops are part of the complex Precambrian bedrock terrane of Wisconsin. This report discusses the metamorphic and tectonic history of the southernmost exposures of Precambrian rocks in Wisconsin. Although the focus is on a single locality, the data obtained have implication for all of the middle Proterozoic geology of southern Wisconsin.

Most of the rocks at Waterloo are massive red to gray quartzites with lesser amounts of interbedded pelitic schist, quartzose schist, and minor amphibolites and pegmatites. The pelitic schists were studied because they provide the best mineralogic and textural indicators of the metamorphic history of the Precambrian in a part of Wisconsin that is otherwise covered by Paleozoic strata. Due to limited exposures, ten core samples were studied in addition to six samples collected from outcrops. Only the core samples (each 10-20 cm in length from 4.0 cm diameter cores) were studied in detail (Table 1). They came from depths of 19.2 m to 333.45 m.

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[1] Department of Geology and Geophysics, University of Wisconsin-Madison

[2] Now at University of Chicago, Department of the Geophysical Sciences, 5734 Ellis Ave., Chicago, Illinois 60637

[3] Now at University of Maine-Orono, Department of Geological Sciences, 110 Boardmon Hall, Orono, Maine 04469

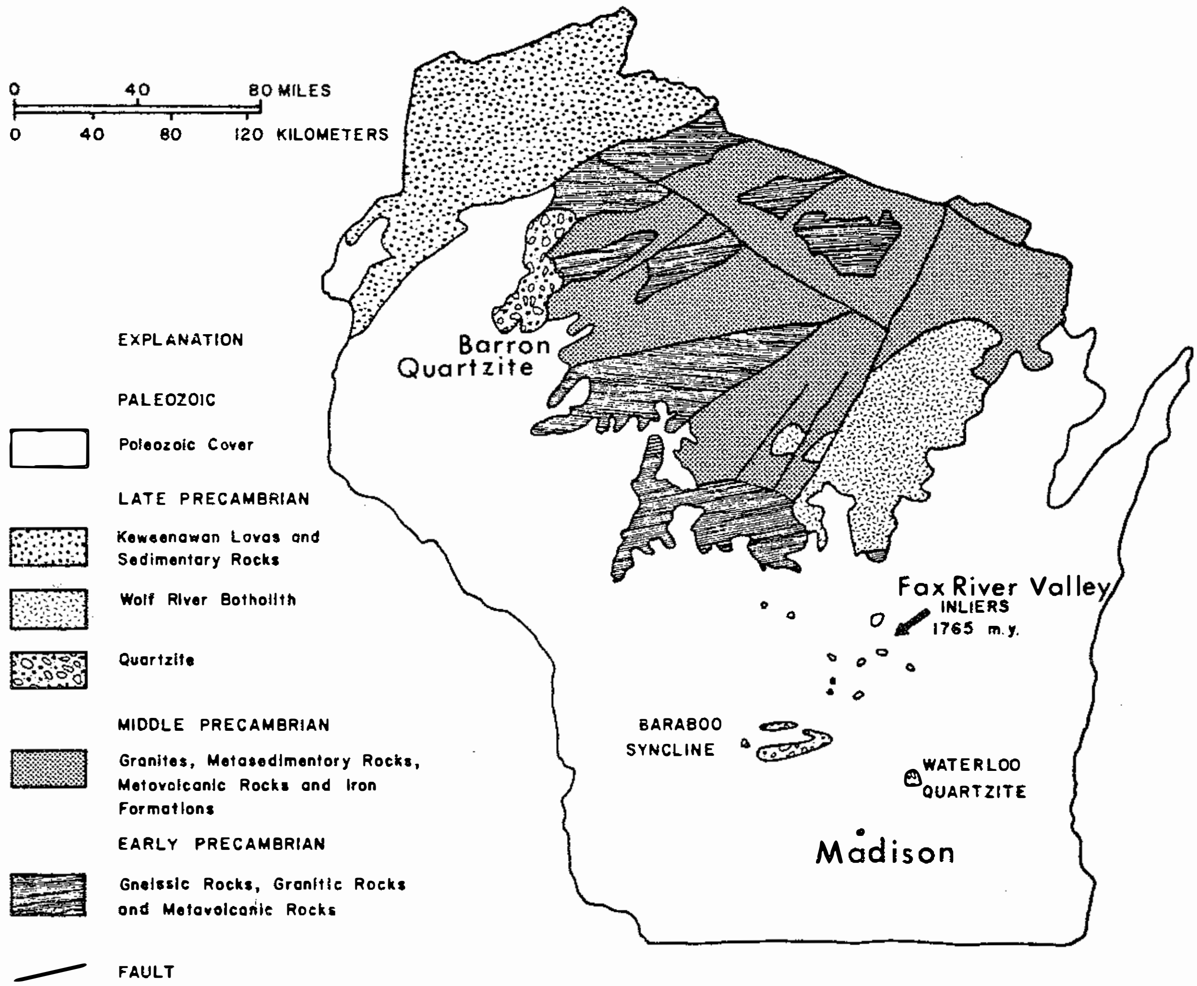

Figure 1. Location of the Waterloo, Baraboo, and Barron Quartzites relative to other major Precambrian features in Wisconsin. Diagram modified slightly from Smith (1978b).

GEOLOGIC SETTING

The Waterloo Quartzite is one of several Precambrian quartzites in Wisconsin. It is lithologically similar and probably stratigraphically equivalent to the Baraboo and Barron Quartzites (Dott and Dalziel, 1972). According to Smith (1978c), the Baraboo Quartzite lies stratigraphically above granites and rhyolites that are chemically similar to rhyolites in the Fox River Valley which have been dated at 1,765 m.y. U-Pb dating of zircons by Banks and Cain (1969) and Van Schmus (1976; 1981), indicate that the main igneous episode of the Penokean Orogeny in Wisconsin occurred far to the north of Waterloo about 1850 to 1900 m.y. ago. Anderson and others (1975) and Smith (1978a) suggested that the rhyolites of the Fox River Valley represent a waning stage of the Penokean Orogeny. More recently, Anderson and others (1978) and Smith (1980) have suggested that the rhyolites were extruded in an anorogenic episode possibly related to crustal extension.

Thus, it would appear that at some time after the last stages of the Penokean Orogeny the Baraboo Quartzite and its stratigraphically equivalent Waterloo Quartzite were deposited. Because of the similarity and proximity (Fig. 1) of the southern Wisconsin quartzites, many workers have concluded that they were part of a sand sheet that was deposited on a major erosional surface of the Penokean granites and the 1,765 m.y. old rhyolites (Dott and Dalziel, 1972; Van Schmus, 1976; Smith, 1978b). Dott and Dalziel (1972) present a brief interpretation of the sedimentologic history of Wisconsin during this time. They suggest that the Waterloo and Baraboo Quartzites represent only a small portion of a thick accumulation of quartz sand deposited on a subsiding, shallow-water continental shelf. More recently, Dott (verbal communication, 1980) has suggested that the lower half of this thick accumulation may be braided river deposits. This thick layer of sand (the Baraboo Quartzite alone is over 1,219 meters thick) (Dott and Dalziel, 1972) extended at least from present Lake Michigan to western South Dakota. According to these authors, most of this thick blanket of quartz sand has subsequently been removed by erosion. The only presently known remnants would be scattered outcrops such as the Baraboo, Waterloo, and Barron Quartzites in Wisconsin and the Sioux Quartzite of South Dakota and Minnesota. The source of this originally large volume of fairly pure quartz sand has never been identified. However, several petrologic factors discussed below enable one to make some reasonable speculations on the source of the clays that formed the schists, and thus the quartz that formed the quartzites.

For the outcrops at Waterloo, the very large modal amounts of muscovite, andalusite, chlorite, and hematite in the pelitic schists, as well as the presence of chloritoid, indicates that these rocks are rich in Al_2O_3 and Fe_2O_3 and to a lesser extent FeO and K_2O. The source for the original sediment may be the extensive area of Penokean and older granitic and metamorphic rocks that are present in northern Wisconsin and Michigan. Weathering and erosion of such rocks could serve as a source for the varying amounts of clays, K_2O, iron oxides, and detrital quartz required to produce the assortment of rocks found at the Waterloo locality. Such a northerly source area would agree with the paleocurrent analyses on the Waterloo Quartzite by Dott and Dalziel (1972). In the case of the Baraboo locality, the shaly interbeds consist mainly of pyrophyllite and presumably are formed by metamorphism of sediment derived from a source producing abundant kaolinite. Thwaites (1931) has presented evidence that significant amounts of kaolinite did form on the Penokean granitic rocks of northern Wisconsin and Michigan. He noted that kaolinite clay horizons, formed on Precambrian rocks and subsequently overlain by Paleozoic strata, were once exploited to a considerable extent for making bricks. Figure 4 of Thwaites' report shows one of these horizons developed at Nekoosa, Wisconsin.

The Waterloo Quartzite presently occurs in a broad, easterly plunging syncline (Buell, 1892; Warner, 1904; and Sumner, 1955), that is folded into a basement of late Penokean granites and 1,765 m.y. old rhyolites. On this structural basis and from the implications of the above discussed correlation of the Baraboo and Waterloo Quartzites, it appears fairly certain that the Waterloo Quartzite is younger than both the Penokean granites and the 1,765 m.y. old rhyolites. Because our observations bear on the events that have affected the rocks since the time of deposition and hence, how these rocks are related to the broader-scale post 1,765 m.y. old events in Wisconsin, further discussion of their geologic history and age will be deferred to the end of this report.

METHODS OF STUDY

Each sample was slabbed and inspected visually in order to observe the megascopic interrelations among foliations, megacrysts and/or pseudomorphs. Subsequently, thin sections and polished sections of each sample were studied by means of transmitted and reflected light. X-ray diffraction scans were run on mica separates in order to ascertain if more than one type of white mica was present. The white mica and opaque minerals were chemically analyzed by means of the University of Wisconsin-Madison ARL Microprobe. The details of these chemical data and its petrologic implications will be presented in a subsequent report.

For the present, emphasis is given to those observations and data which bear more on geologic rather than petrologic aspects. Specifically, these will include features such as cross-cutting relations among foliations, overprinting by megacrysts, and pseudomorphing of megacrysts. The interrelationships among such features enables one to ascertain the relative order of tectonic and metamorphic events.

PETROGRAPHY AND MINERALOGY

Only two essential mineral assemblages have been recognized in the pelitic schists (see Table 1). One of these consists of muscovite, quartz, chlorite, hematite, $\pm$ plagioclase with minor amounts of tourmaline, apatite, rutile, zircon, and a high relief, high birefringence mineral which is probably in the epidote group. The other assemblage is similar but also contains andalusite, chloritoid, and plagioclase.

In both assemblages, the modal amounts of each mineral vary considerably from specimen to specimen. Moreover, in many samples the presence of two types of pseudomorphs suggests that other assemblages were previously present. The lack of biotite in all samples is presumably due to bulk composition (too high Al_2O_3) rather than to metamorphic conditions.

Table 1. Mineralogy of specimens from Waterloo, Wisconsin.

	CVG-B55	CVG-B56	CVG-B57	CVG-B58	CVG-B59	CVG-B60	CVG-B61	CVG-B62	CVG-B63	CVG-B64	CVG-B65
Mineral											
Quartz	√	√	√	√	√	√	A	√	√	√	A
Plagioclase	√	√	?	√	√	?	M	√	√	√	M
Muscovite	√	√	√	√	√	√	P	√	√	√	P
Chlorite	√	√	√	√	?	√	H	√		√	H
Andalusite	√				√	√	I		?		I
Chloritoid	√				?		B				B
Opaques (Hem+Mag)	√	√	√	√	√	√	O	√	√	√	O
Rutile	?	√	√	√	√	√	L		√	√	L
							I				I
Alteration Minerals							T				T
Kaolinite	√				√	√	E				E
Hematite "Dust"	√	√			√	√			√		
Accessory Minerals											
Tourmaline	√	√	√	√	√	√		√	√		
Apatite	√	√	√	√	√	√		√	√	√	
Zircon	√	√	√					√			
Epidote Mineral	?	√			√	√		?	√	√	

√ = mineral present; ?=question if present; blank = not seen.

All specimens display a strong foliation of the groundmass minerals (muscovite, quartz, plagioclase, hematite, and to a minor extent chlorite) with highly-oriented muscovite laths providing the main foliation. This strong foliation appears to be the earliest and, following the classification of Spry (1969), is designated as S_1. It is present in all specimens and usually is the only foliation that is easily recognized in hand specimen. Two later strain-slip cleavages (Ayrton and Ramsey, 1974), defined by the alignment and kink banding of muscovite, can also be recognized and are designated as S_2 and S_3. All three S surfaces are shown in Figure 2. As seen on this Figure, S_3 which is only weakly and sporadically developed, is recognizable mainly in terms of minor kinking of some of the coarser muscovite plates which overprint the groundmass matrix. S_2 can be recognized in about half of the specimens. In at least three samples it is readily apparent even in hand specimen (especially sample WTL-1). The spacing of the strain-slip planes of S_2 is on the scale of a few mm. However, any bending of muscovite laths which may have occurred during the slip-cleaving event has now been obscured by recrustallization. The resulting straight laths of groundmass muscovite produces a polygonal texture (Zwart, 1962) which is apparent when viewed with crossed nicols. Typically S_2 occurs at approximately 90° to S_1 (See Fig. 2).

Muscovite

Although muscovite is dominantly a groundmass mineral, it also occurs as coarser laths that crosscut and overprint the groundmass foliations, S_1 and S_2. In some cases the coarser muscovite laths are oriented parallel to S_2. Figures 2, 3, and 5 show some of these features. The groundmass laths are usually less than 0.1 mm in length whereas the larger laths are up to 0.3 mm by 1.2 mm in size.

X-ray diffraction scans indicate that muscovite is the only "white mica" in the pelitic schists. No peaks of paragonite, margarite, or pyrophyllite were detected. The modal amount of muscovite ranges from less than 10 percent in the quartzose schists to as high as 85 percent in the mica-rich samples.

Quartz and Plagioclase

Quartz and plagioclase are restricted to the groundmass. The plagioclase is untwinned, contains various inclusions, and has rather indistinct grain boundaries. It appears to be present in minor amounts in most specimens (usually less than 2 percent), but because of its indistinct appearance it could not be recognized in some specimens. In no cases could rigorous estimates of its abundance be made. Quartz occurs in several different textural types. Normal (that is, unstrained) quartz is most abundant, but in some samples quartz has undulose extinction or a "cross hatching," which is indicative of strain in the crystal structure (Spry, 1969). In a few cases, quartz grains occur in thin, 0.5 mm wide veinlets that crosscut all other features in the specimens. Apparently these veinlets were formed very late in the tectonic and metamorphic history of the Waterloo Quartzite. The modal amounts of quartz range from a few percent in highly micaceous specimens to as much as 90 percent in some of the quartzose schists.

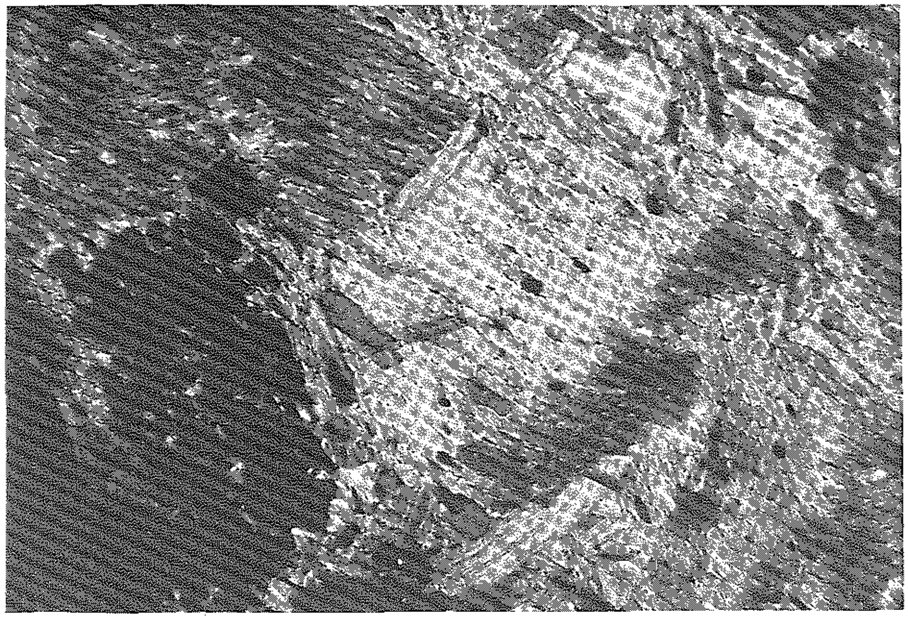

Figure 2. S_1 foliation (trending from upper left to lower right) and annealed slip cleavage S_2 (trending from lower left to upper right and shown by the bands of extinguished and non-extinguished muscovite). Large muscovite lath in the lower center overprints S_1 and S_2 and has been kinked by a subsequent slip cleavage, S_3 which is nearly parallel to S_1. Mineral in lower left is andalusite. Specimen: CVG-B55. Photo taken with nicols crossed; long direction is 2.4 mm.

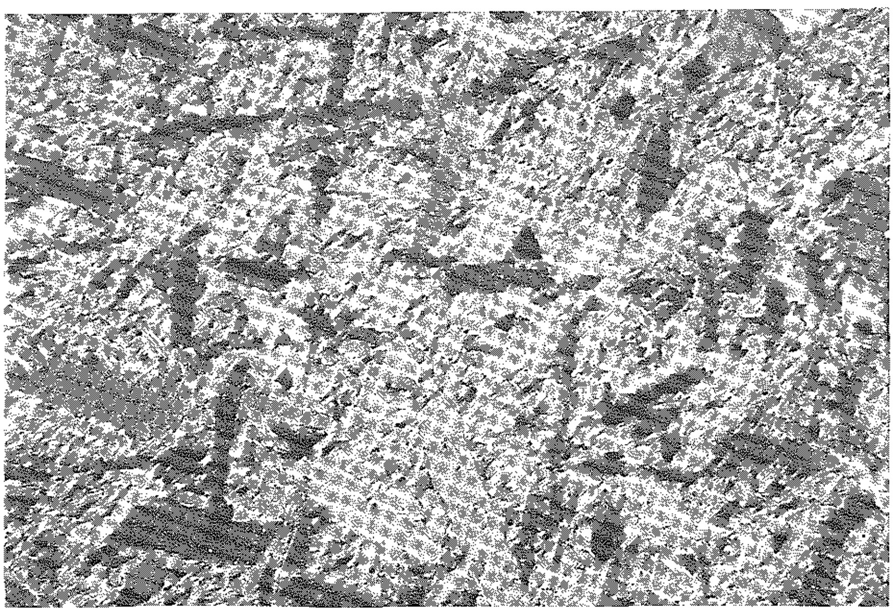

Figure 3. Large muscovite laths overprinting groundmass foliation to produce a "Herringbone" pattern. Specimen: CVG-B58; nicols crossed; long direction is 2.4 mm.

Chlorite

Chlorite is present in modal amounts ranging up to 10 percent. Under crossed nicols it varies in color from anomalous blue in some specimens to anomalous brown in others. According to the criteria developed by Albee (1962), the blue chlorite is Fe-rich and the brown chlorite is Mg-rich. Texturally chlorite occurs in three different varieties: (1) fine-grained laths in the groundmass foliation; (2) coarse laths or plates (to 1.5 mm) or both which crosscut and overprint the groundmass; and (3) coarse plates and laths intimately associated with the two different types of pseudomorphs.

Andalusite

Andalusite occurs as euhedral megacrysts up to 0.5 cm in width. In hand specimen, it occurs as reddish-colored, square prisms which are more deeply colored in the outer portions. In thin section, the megacrysts are seen to contain abundant poikilitic inclusions and to truncate and overprint both S_1 and S_2 (Fig. 2). In most cases, the andalusite-bearing samples do not contain any of the pseudomorphs mentioned above. However, some exceptions do occur, and in one specimen (WTL-2), andalusite megacrysts are included within the larger of the two pseudomorph types. In some cases, the core portion of andalusite contains much greater amounts of fine-grained inclusions which form patterns simulating those in the groundmass (Fig. 7 and 9).

Two different types of partial pseudomorphs (after andalusite) have formed. The extent of this pseudomorphing varies from specimen to specimen as well as from grain to grain in a given specimen. One type consists of small, cross-cutting veinlets of moderately fine-grained muscovite (Fig. 9). These veinlets continue into the groundmass and may represent cracks along which andalusite has been converted to muscovite. The other type of pseudomorph after andalusite is restricted to the outer few mm of some of the megacrysts (Fig. 7 and 8). It consists of kaolinite as indicated by its optical properties and the presence of a 7.35 °A peak on one of the diffractometer scans. The kaolinite is intimately intergrown with very fine grained hematite and possibly results from a late hydration reaction such as:

$$Al_2SiO_5 + 2H_2O + SiO_2 \rightleftharpoons Al_2(Si_2O_5)(OH)_4$$

The concentration of hematite in these kaolinite rims may be responsible for the red color mentioned above.

Chloritoid

Chloritoid is present in some of the andalusite-bearing specimens. It occurs as prisms approximately 0.05 mm to 0.3 mm in length and occasionally as large as 0.5 mm. Commonly, the prisms form bundles or radiating clusters. At the most, chloritoid accounts for about 2 modal percent of a given specimen. Typically it has a weakly pleochroic green color, high relief, and prominent polysynthetic twinning. In some samples the chloritoid has been partially to totally altered to hematite and possibly other unidentified iron oxide minerals. Although no unequivocal textural evidence is present, the chloritoid appears to have grown contemporaneously with andalusite. According to Winkler (1979), the presence of chloritoid suggests bulk compositions with a relatively high Fe/Fe+Mg ratio, high Al_2O_3, and low total alkalies.

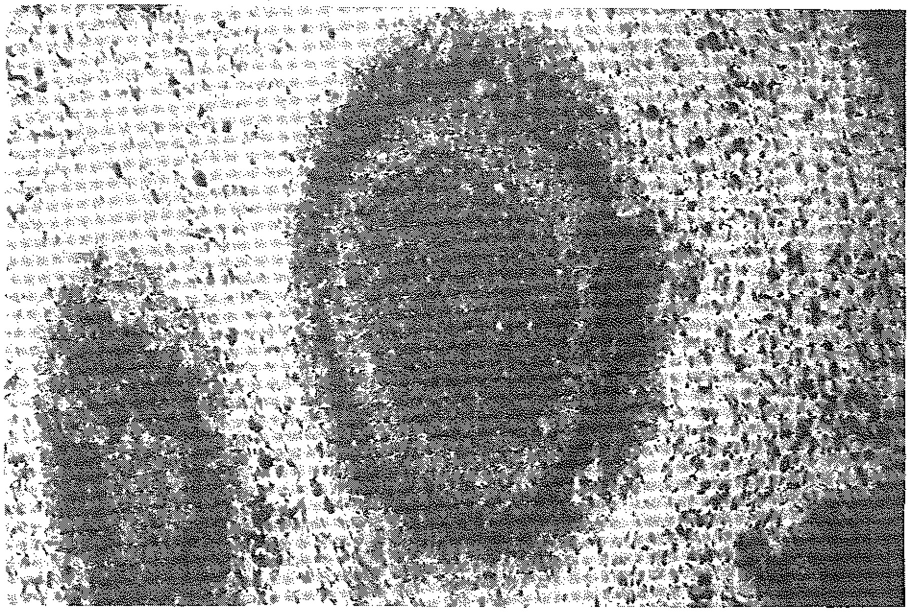

Figure 4. Type I pseudomorph. showing concentric banding. Specimen: CVG-B62; nicols crossed; long direction is 6.0 mm.

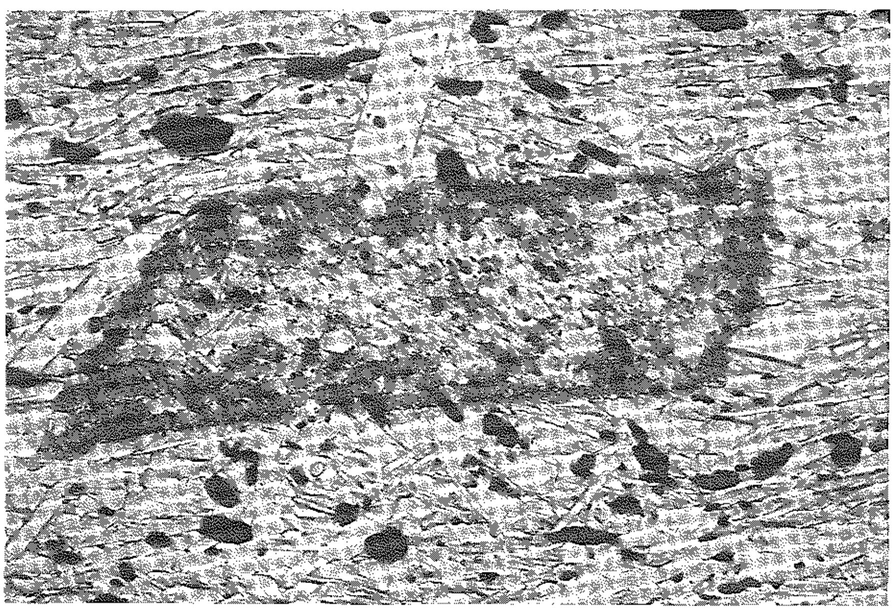

Figure 5. Type II pseudomorph. Outer dark rim is mainly chlorite. S_2 is parallel to the coarse muscovite laths and S_1 parallel to the groundmass muscovite laths. Specimen: CVG-B57; Plane light; long direction is 1.0 mm.

Iron Oxides

Hematite and magnetite are the only opaque minerals that have been identified. Because the thin sections were cut perpendicular to foliation, the hematite appears as lath shaped subhedra. Most specimens contain as much as 20 modal percent of hematite and only minor magnetite. The magnetite occurs as small "island like" patches within the larger hematite laths.

Some of the hematite, as described in the discussion of andalusite, occurs as finely dispersed grains, at least some of which may be related to a later alteration event. However, most hematite is present as coarser laths (generally less than 0.1 mm long) which are parallel to S_1 but also follow the crinkles produced by S_2. In the andalusite + chloritoid-bearing specimens some of these laths are euhedral and up to 0.8 mm in length.

Cursory probe work indicates significant amounts of $FeTiO_3$ dissolved in the hematite laths that are 0.1 mm and smaller. According to Rumble (1976) these laths should be classified as titanhematites. In contrast, the coarsest laths (to 0.8 mm) and their associated magnetite do not appear to contain significant amounts of TiO_2.

Other Minerals

Except in one specimen, tourmaline is present only as an accessory mineral. In specimen CVG-B55 it amounts to about 10 modal percent and occurs as prisms ranging in length from 0.02 mm up to 0.8 mm. In the other specimens it occurs only as prisms less than 0.02 mm long. In all cases the tourmaline is blue-green. Apatite, epidote, rutile, and zircon are minor accessory minerals in virtually all specimens. However, in one specimen small needles and irregular grains of rutile make up about 3 modal percent. Zircon occurs as tiny grains in chlorite and is easily detected due to the development of pleochroic halos.

Pseudomorphs (non-andalusite)

In addition to the partial pseudomorphing of andalusite, two other types of pseudomorphs are present in several specimens. Unually both types are present together in a given specimen. Type I pseudomorphs are ovoid in shape and range from 0.5 to 1.0 cm in diameter. They consist mainly of moderately fine-grained chlorite, muscovite, quartz, and opaques (hematite?). Microscopically and megascopically these pseudomorphs display a complex concentric zonation. In hand specimen the zonation is defined by varying shades of green with a reddish core in some cases (due to finely disseminated hematite?). In thin section it is evident that these concentric, diffuse bands are due to variation in the relative amounts of the minerals that make up the pseudomorphs. As many as six bands of fairly uniform thickness (excluding the core) are present in some of them. Within the pseudomorphs, the chlorite, muscovite, and quartz are about as coarse-grained as they are in the groundmass, but in some cases the chlorite in the outer zone is coarser grained. This implies that the pseudomorphs probably formed at temperatures high enough to facilitate significant recrystallization. Figure 4 shows one of these pseudomorphs with at least three recognizable zones. Identification of the pseudomorph precursors has not been possible, but because of their ovoidal shape and abundance of chlorite, it is presumed that the original mineral was an equant, Fe-Mg phase

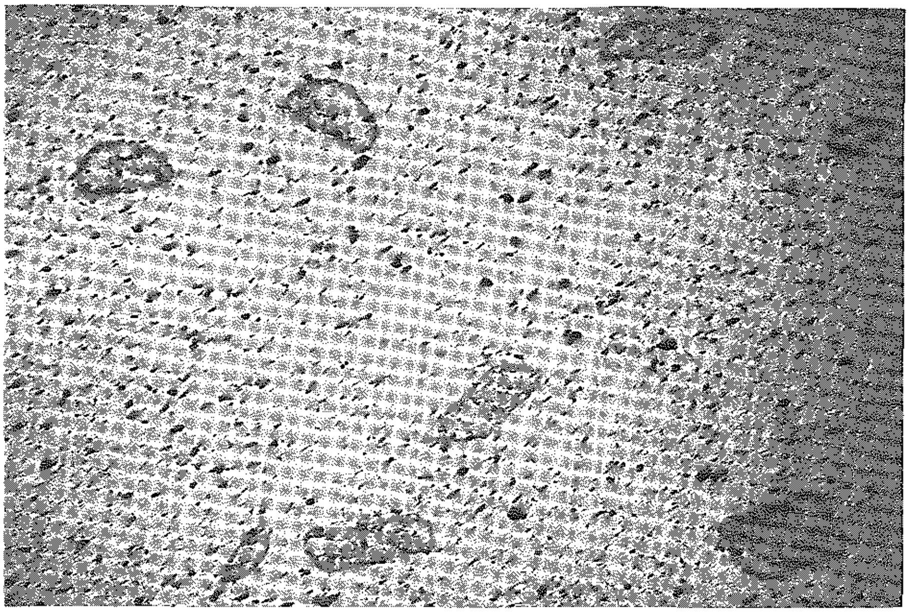

Figure 6. Type II pseudomorphs. Note how they overprint this groundmass.
Specimen: CVG-B57; Plane light; long direction is 6.0 mm.

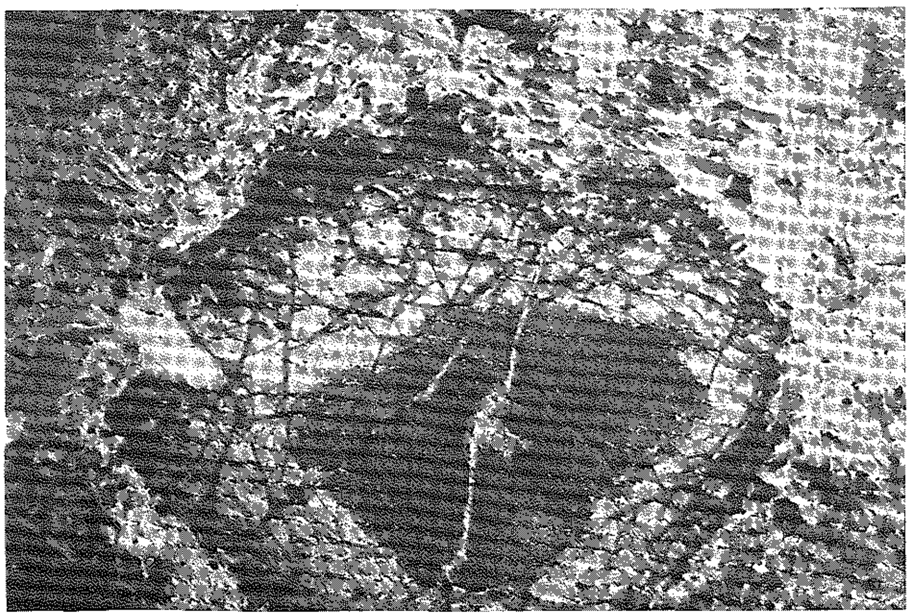

Figure 7. Andalusite megacryst. Outer dark zone is kaolinite replacing andalusite. The inner dark zone consists of andalusite plus abundant inclusions of quartz and muscovite. These inclusions outline an earlier fine-grained groundmass foliation which has been overprinted. Specimen CVG-B55; Crossed nicols; long direction is 6.0mm.

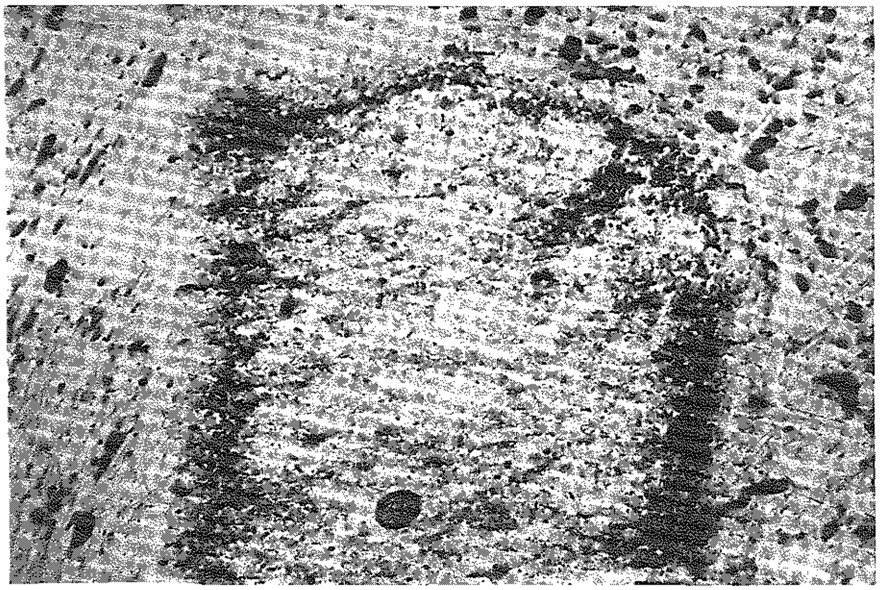

Figure 8. Partially altered andalusite megacryst. Outer dark rim is mainly hematite. Specimen: CVA-B59; Plane light; long direction is 2.4 mm.

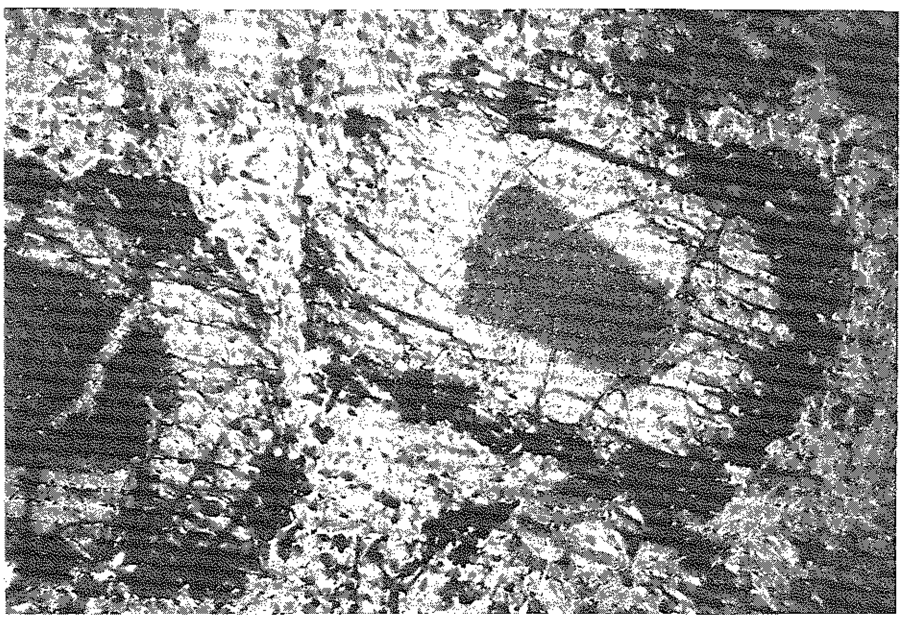

Figure 9. Andalusite megacrysts. Note late, crosscutting veinlets consisting of fine-grained muscovite-trending NE to SW in the central portion of the megacryst on the left. Specimen: CVG-B55; Crossed nicols; long direction is 6.0 mm.

such as garnet or cordierite. Moreover, it was not possible to determine whether the concentric bands reflect original zonation in the precursor mineral or some diffusion mechanism that occurred during formation of the pseudomorphs.

Type II pseudomorphs are much smaller (1.5 mm by 0.5 mm) and display a distinctly prismatic shape (Fig. 5 and 6). Their overall shape, in some cases involving twinning, suggests that they may have formed after staurolite. These pseudomorphs consist of relatively coarse-grained chlorite, muscovite, and quartz plus finely-dispersed opaque minerals. In most cases these minerals tend to concentrate in various combinations such that the pseudomorph displays some degree of concentric banding. However, in no cases are the bands as pronounced as in the case of the Type I pseudomorphs. In neither case does there appear to be a systematic pattern of zonation that persists from specimen to specimen.

Both types of pseudomorphs clearly truncate S_1 and S_2, thereby indicating that the original minerals also post-date the formation of S_1 and S_2. In one specimen the pattern or distribution of coarser opaque grains in the groundmass can be seen to persist in an undisturbed fashion completely through one of the Type I pseudomorphs. These latter observations plus the fact that both Type I and Type II pseudomorphs consist of fairly coarse, randomly oriented muscovite and chlorite, suggests that not only were two separate metamorphic events required to produce the original minerals and their subsequent pseudomorphs but that both were post-deformational events. Moreover, both must have involved fairly intensive crystallization but with the first being the more intense. The post-deformational nature of the first event is also suggested by the lack of any orientation of andalusite (or the two precursor minerals) with respect to S_1 or S_2.

TECTONIC AND METAMORPHIC HISTORY

The above-described interrelationships of minerals and textures tentatively suggest a sequence of metamorphic and structural events that have affected the Waterloo rocks. Because late, widely-spaced brittle shears which are unassociated with any recrystallization may not have any effect on textures, the suggested sequence of events may not include such activity. The sequence suggested below is based on the manner in which mineral grains, foliations, and pseudomorphs are interrelated. An attempt has been made to propose a sequence that is as simple as possible so as to avoid making assumptions not required by the data.

The proposed sequence of events is:

(1) The rocks were deformed (D_1) producing S_1, the main foliation as defined by the orientation of fine-grained muscovite laths. Probably this was mainly a tectonic event, but it may have been accompanied by low-grade crystallization such as during the formation of a slaty cleavage.

(2) Another deformation (D_2) occurred and produced a closely spaced strain slip cleavage, S_2. S_2, like S_1, is defined by the laths of fine-grained muscovite and typically is at a high angle to S_1. As with D_1, any metamorphism associated with D_2 must have been low-grade.

Depending upon whether the few amphibolites encountered in the core log are dikes or sills instead of lava flows, they could have been emplaced at any time through event #1. According to Haimson (1978) these mafic bodies are sills.

(3) The next event was a high-grade, largely static metamorphism which produced the euhedral megacrysts of andalusite and chloritoid. Because this was the first major thermal event, it is designated as M_1. It would seem likely that the two unidentified minerals which are now pseudomorphed also formed during this event. During M_1, any bending of the micas which may have occurred during formation of S_2, was probably eliminated due to recrystallization. The resulting straight mica laths form arches of a sort described by Zwart (1962) as polygonal texture. The amphibolites mentioned above may have formed during this event. This stage clearly postdated the two deformational events as the andalusite megacrysts overprint the S_1 and S_2 foliations. As discussed in the last section, this megacryst forming event is interpreted as a thermal culmination following the two deformations in a single thermo-tectonic event.

(4) The next event was another moderately high-grade, static metamorphism (M_2). This event produced the Types I and II pseudomorphs. Some partial pseudomorphing of chloritoid also occurred during this event. The muscovite which partially replaces some andalusite may be contemporaneous with M_2, and the coarse chlorite and muscovite that overprints the groundmass foliations probably formed at this time also.

As discussed in the next section, the P,T conditions for M_1 can be estimated roughly, but due to the lack of any indicator minerals, such estimates are less rigorous for M_2. However, it can be said that M_2 was a pervasive event that resulted in complete pseudomorphing of some presumably Fe-Mg mineral that was up to 1 cm in size. Moreover, it also involved sufficient recrystallization such that fairly coarse-grained chlorite and muscovite were produced.

(5) The last event (or events) caused only minor effects which are not evident in all specimens. It produced the kaolinite rims around some of the andalusite and the very minor kinking (S_3) that effects a few large chlorite and muscovite laths. The few thin quartz veinlets crosscutting some specimens probably formed during this event (or events). It seems likely that these various effects are due mainly to late, low-temperature, brittle fracturing. Moreover, one specimen, CVG-B64 which is highly sheared, may be related to a larger cataclastic zone.

METAMORPHIC CONDITIONS

Inasmuch as two of the minerals formed during M_1 are now completely pseudomorphed (and not rigorously identifiable), it is not possible to ascertain accurately the prevailing P,T conditions. Nonetheless, the presence of andalusite, muscovite, and chloritoid combined with the knowledge that the bulk composition is highly aluminous makes it possible to estimate the limiting P,T conditions during M_1. The aluminosilicate phase diagram of Holdaway (1971) was used in making these estimates. It was also assumed that $P_{fluid} = P_{Total} = P_{H_2O}$. This is a reasonable assumption because: (1) there are no C or CO_2-bearing phases present, (2) the high fO_2 implied by the presence of hematite would require that any H in the fluid be combined with O to form H_2O, and (3) the breakdown of the various clays (kaolinite, pyrophyllite) during M_1 would liberate abundant H_2O.

Figure 10 shows a P,T diagram with those experimental curves that are relevant to the Waterloo rocks. The presence of andalusite clearly implies that during M_1 these rocks recrystallized at a maximum of 3.8 kb pressure within the P,T field shown for andalusite on Figure 10.

Although no pyrophyllite has been observed in the Waterloo rocks, the high Al_2O_3 content implied by the abundance of andalusite and the absence of biotite, suggests that at the appropriate grade, this mineral would be present. Moreover, in the shaly interbeds of the supposedly stratigraphic equivalent Baraboo Quartzite, pyrophyllite is abundant. Hence, it would seem reasonable to suggest that the Waterloo rocks crystallized at some temperature (depending upon the pressure) above the pyrophyllite breakdown curve shown on Figure 10.

On the other hand, the presence of chloritoid in several specimens clearly suggests that the maximum temperature attained had to be below the upper stability limit of chloritoid in quartz + muscovite-bearing rocks. On Figure 10 the stability curves of Fe-chloritoid + quartz + O_2 and Fe-chloritoid + Al_2SiO_5 + O_2 are from Richardson (1968). Because of the Fe-rich aspect of the Waterloo rocks, use of these iron-end-member chloritoid stability curves probably provides a reasonable approximation of the bulk composition of the natural specimens. It is therefore evident that the occurrence of chloritoid + quartz in the Waterloo pelitic schists implies that these rocks formed at temperatures below those of the two chloritoid curves shown on Figure 10. According to Grieve and Fawcett (1974) and Hoschek (1969), variation of fO_2 will have some effect on the position of the chloritoid curves, but the effect will not be extreme. For the purposes of this paper this effect will be ignored.

In summary, based on the above discussion, it is possible to estimate roughly that during M_1, $P_{Total} = P_{H_2O} < 3.8$kb and temperatures were between 350 °C and 550 °C. Based on the degree of crystallization and thoroughly penetrative fabric, it would seem unlikely that these rocks formed in a near surface environment. Hence, it is assumed that the minimum pressure was at least greater than 1 kb (equivalent to a depth of 3.6 km). If the Type I and II pseudomorphs were originally minerals such as staurolite or cordierite, then the temperatures would have had to be at least high enough to be in the stability fields of these minerals. This would provide a more refined estimate of the lower temperature limit of M_1.

As mentioned previously, it is not feasible to say much about the metamorphic conditions during M_2. It seems likely that the T of M_2 was less than that of M_1. However, the thorough degree of recrystallization of the Type I and II pseudomorphs suggests that the T of M_2 must have been high enough to overcome any kinetic barriers to recrystallization of the original phases,

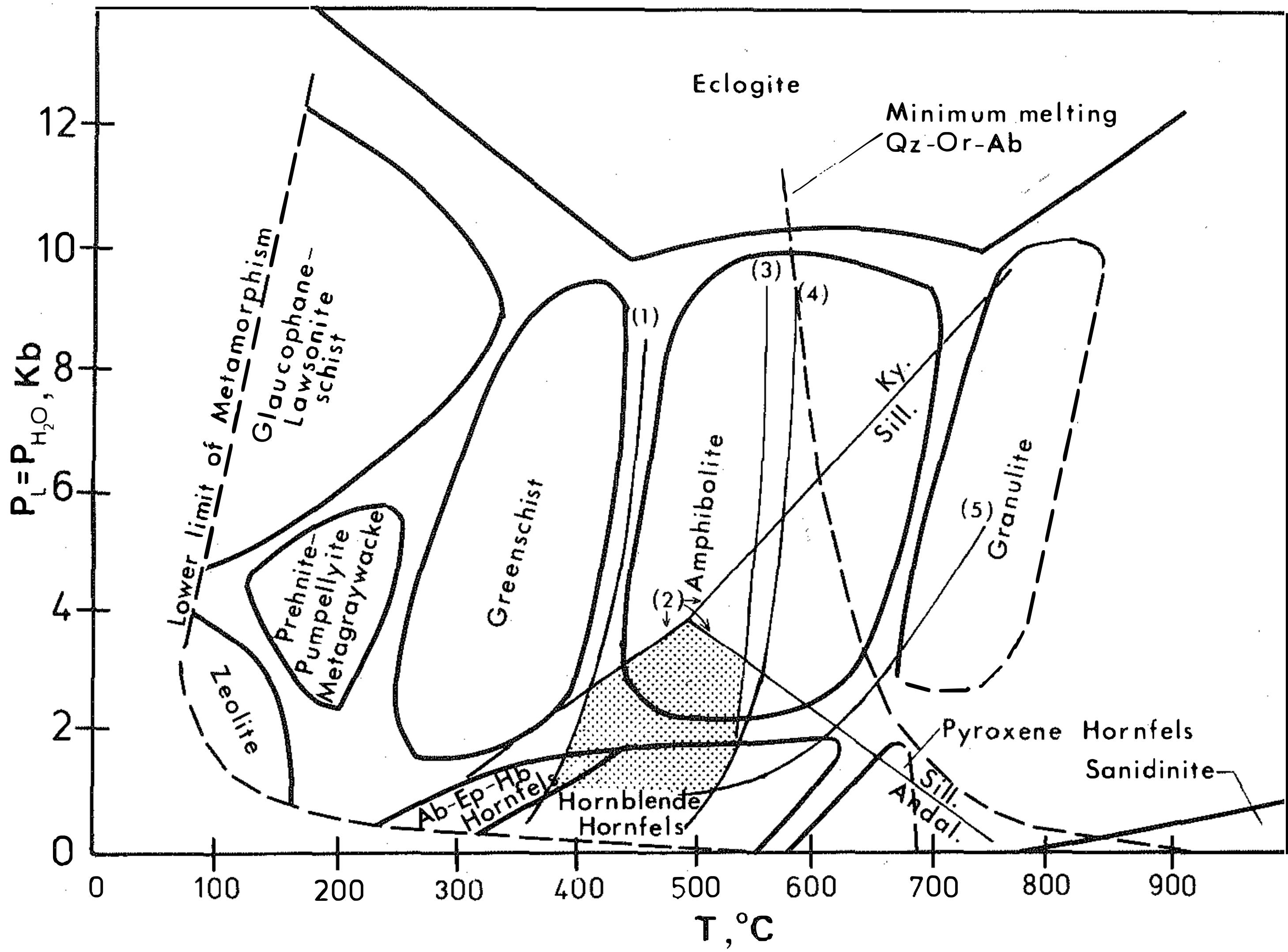

Figure 10. PT curves and facies zones bearing on the metamorphic conditions which have affected the rocks at Waterloo, Wisconsin. Source and identification of information shown include:
Curve (1). Upper stability limit of pyrophyllite in the presence of quartz, (Kerrick, 1968).
Curve (2). PT curves for the aluminosilicate polymorphs, (Holdaway, 1971).
Curve (3). Upper stability limit of the asemblage Fe-chloritoid + Al_2SiO_5+O_2, (Richardson, 1968).
Curve (4). Stability limit of Fe-chloritoid + SiO_2 + O_2, (Richardson, 1968).
Curve (5). Upper stability limit of muscovite + SiO_2, (Kerrick, 1972).

Facies Zones. Taken from Turner (1968).

Stippled area shows the metamorphic conditions that may have affected the Waterloo area.

including the diffusion required to form the present minerals in the pseudomorphs. If the assemblage andalusite $\pm$ chloritoid + muscovite + chlorite + quartz remained stable during M_2, then the broad range of P,T conditions discussed above for M_1 would also apply to M_2.

REGIONAL IMPLICATIONS

In this section discussion will focus on two points, (1) a comparison between the petrologic conditions which prevailed in the Waterloo and Baraboo areas, and (2) an attempt to relate the events listed above with the region wide events recognized or suggested by other workers.

Regarding the first point, it appears that the metamorphic conditions at Baraboo were significantly less intense than those at Waterloo. For example, andalusite has never been verified at Baraboo but pyrophyllite is quite abundant. Because of the pyrophyllite at Baraboo, Dalziel and Dott (1970) suggest metamorphic temperatures below 430 °C. These suggested lower temperatures in that area are fully consistent with the relatively minor recrystallization which has affected those rocks. Assuming that it was M_1 which affected both areas and that it was a large-scale regional event (see discussion below), then the temperatures of metamorphism for these stratigraphically equivalent rocks *may* have differed by as much as 120 °C -- for outcrops some 65 km apart.

As for the second point, arguments were advanced in an early section of this report which suggested that the deposition of the Baraboo and Waterloo Quartzites postdated both the Penokean Orogeny and the 1,765 m.y. old rhyolites. Hence, based on the observations on D_1, D_2, M_1, and M_2 which have been discussed in this paper, it would seem possible that significant (probably regional) tectonic and metamorphic events may have occurred in southern Wisconsin subsequent to the Penokean Orogeny and extrusion of the 1,765 m.y. old rhyolites (See also Van Schmus and others, 1975a).

Some of the events subsequent to the formation of the 1,765 m.y. old rhyolites that have been suggested for Wisconsin include:

(a) Smith (1978b) has suggested that the rhyolites were folded sometime between 1,765 m.y. and 1,650 m.y. ago. Subsequently, the sands that later became the Baraboo and Waterloo Quartzites were deposited over the folded rhyolites.

(b) Smith (1978b) also suggested that the Waterloo Quartzite was deformed to its present attitude during a regional metamorphic event 1,650 m.y. ago. This corresponds with a time of widespread regional resetting of Rb-Sr systems in much of Wisconsin (Van Schmus and others, 1975a). More recently, Van Schmus (1978), using new decay constants, has modified the time of this resetting to 1,630 m.y. ago.

(c) The Wolf River Batholith was intruded about 1,500 m.y. ago and the Keweenawan basalts were extruded and diabase dikes intruded 1,115 m.y. ago (Van Schmus and others, 1975B) (See Fig. 1 for locations).

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