THE STRUCTURE AND PETROLOGY OF PRECAMBRIAN METAMORPHIC ROCK UNITS, NORTHWESTERN MARATHON COUNTY, WISCONSIN

A THESIS

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ELIZABETH ANN PALMER

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ABSTRACT

Precambrian metamorphic units in northwestern Marathon County, Wisconsin, consist of an extrusive region composed of basaltic to felsic metavolcanics, and a gneissic region composed of granitic to dioritic gneisses. Both the metavolcanic and gneissic regions have been intruded by felsic plutonic rocks. The metavolcanic region has also been intruded by mafic units. The contact between these two terranes is a cataclastic zone which trends approximately N75^{o}E through Athens, Wisconsin. The zone itself appears to have gradational boundaries and may be anastamosing.

Structural and petrologic investigations indicate two deformational phases in the area accompanied by varying degrees of recrystallization. The first deformational phase is represented by quartzofeldspathic and mafic mineral assemblages diagnostic of amphibolite facies metamorphism. Relationships in the gneisses generally indicate textural disequilibrium although locally equilibrium textures are found. The presence of migmatites and complex folds is further evidence for regional metamorphism involving deformation at high temperatures and pressures.

The first deformational phase is also represented by the metamorphism of volcanic rocks to greenschist facies and local deformation. Where the rocks are not highly deformed, primary volcanic textures and structures are well preserved.

The development of similar penetrative structural trends in both terranes is further evidence for the first deformational phase. The structural features suggests a strain history in the study area such that maximum elongation (extension) occurred parallel to lineation in the plane of foliation, while shortening (flattening) occurred in a northwest-southeast direction, perpendicular to foliation. Strain results indicate the rocks were shortened up to 40 percent of their original length.

The second deformational phase is represented by an assortment of cataclastic rocks derived from both terranes, the local development of a linear fabric associated with cataclasis, slickenside surfaces, and the development of two major joint systems. The major joint system trends northwest-southeast, perpendicular to foliation, while a second system trends northeast-southwest, parallel with foliation. If these joint sets are tensional features, the stress field which caused their development would be consistent with the stress field which developed the foliation during the first deformational phase.

The intrusion of tonalitic to granitic plutonic rocks into the gneissic and volcanic terranes probably occurred about 1840 m.y. ago. Pervasive cataclastic textures in the plutons suggests deformation was operative after the emplacement of the intrusions.

The next event in the area was the emplacement and local recrystallization to greenschist facies metamorphism of mafic rocks. These units intrude the volcanic terrane and trend subparallel to the cataclastic zone. Following this, quartz veins were introduced into these and associated units. The quartz veins and their host rocks were then locally faulted.

The petrologic and structural evidence in northwestern Marathon County, Wisconsin, define a high-grade metamorphic complex which is lithologically distinct and tectonically separate from a lower-grade suprastructure. The contact between the two terranes is defined by a relatively thin boundary fault zone having a metamorphic gradient with complex shearing.

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INTRODUCTION

Geographic and Geologic Setting

Marathon County is located in north central Wisconsin (Fig. 1). The present study is situated in northwestern Marathon County in the Civil Townships of Halsey, Rietbrock, Johnson, Bern, Hamburg, and Rib Falls. The area encompasses over 300 square kilometers and is centered near Athens, Wisconsin, which is located approximately 37 km northwest of Wausau, Wisconsin.

The study area lies on the southern margin of the Canadian Shield, an extensive low-lying region of Precambrian rocks that composes the exposed part of the North American craton. The area is underlain by Precambrian igneous and metamorphic rocks traversed by several large northeast- and northwest-trending zones of cataclasis. Glacial deposits of irregular thickness and varying type and provenance cover the Precambrian in much of the region.

Regional Precambrian Geology

The Lake Superior region contains rocks belonging to each of the three major subdivisions of the Precambrian. Morey and Sims (1976), and Sims (1976), developed a two-terrane concept for the Precambrian geology in the Lake Superior area. Essentially, the northern

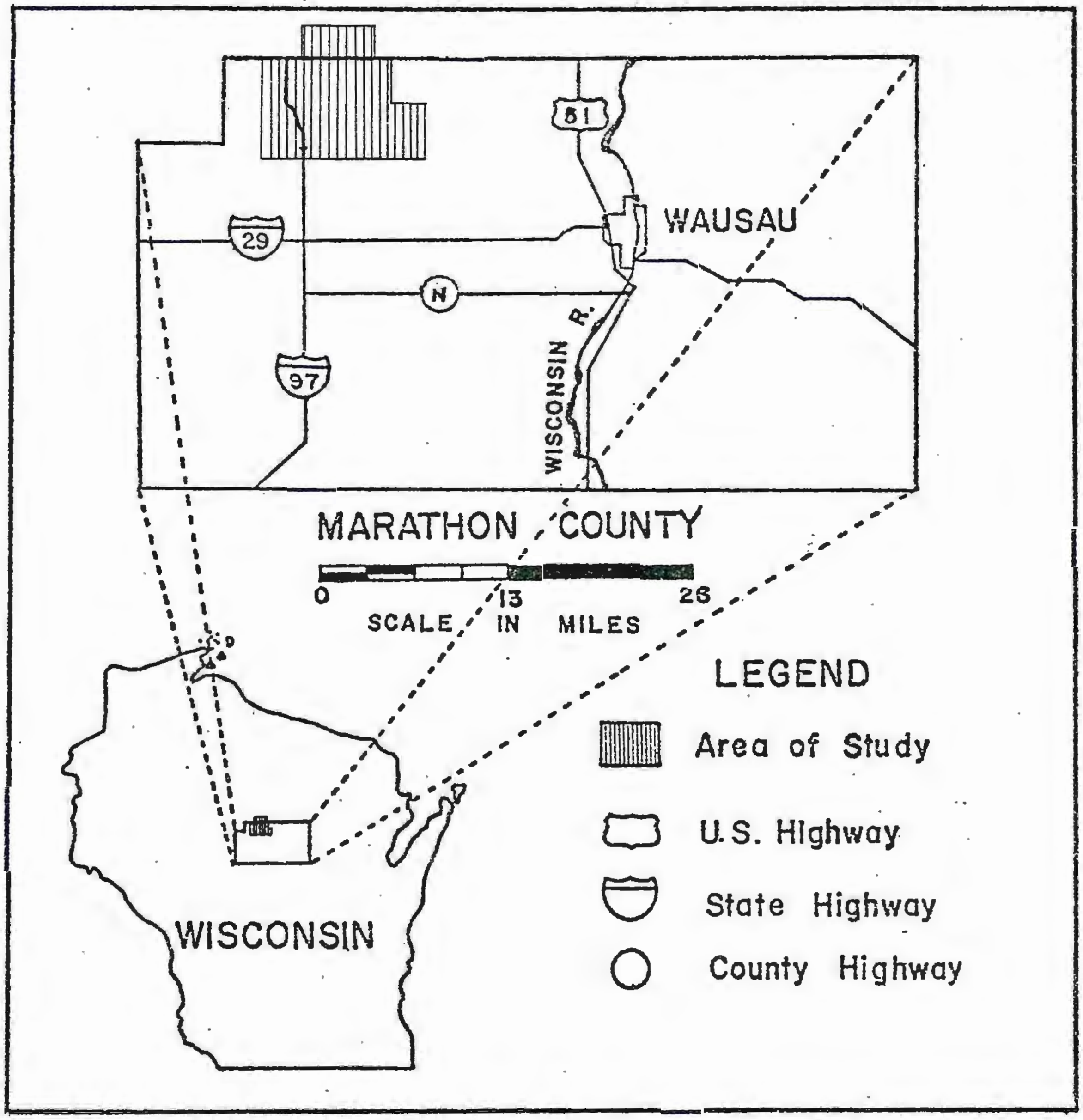

Figure 1. Index map of area studied, Northwestern Marathon County, Wisconsin.

parts of Minnesota, Wisconsin, and Michigan are underlain by a granite-greenstone terrane about 2,700 million years old. Gneissic terrane underlies the southern parts of those states and is dated at over 3.5 billion years in Minnesota, and at least 3.2 billion years in Wisconsin and Michigan (Sims and Peterman, 1976; Van Schmus and Anderson, 1977; and Peterman, Zartman and Sims, 1976). The gneissic terrane has behaved as a mobile belt that was reactivated many times (LaBerge and Mudrey, 1979). The most recent significant reactivation was during the Middle Precambrian giving rise to the Penokean (?) period of metamorphism and deformation. Based on geophysics, outcrop data, and sparse geochronology, Figure 2 illustrates the model for northern Wisconsin.

In Wisconsin, several gneisses have been dated as Early Precambrian (Archean or Precambrian W) (Sims, Peterman and Prinz, 1977). No radiometric age dates are available from the gneisses in Marathon County however, thus their age is uncertain. Van Schmus and Anderson (1977) have reported an age of more than 2800 m.y. for migmatitic gneisses at Pittsville, 25 km south of Marathon County. Gneisses within the present study area may be part of a high-grade metamorphic terrane that extends at least 60 miles to the west (LaBerge, 1980). The gneisses mineralogically resemble those of the "Chippewa Amphibolite Complex" described by Myers (1974) from exposures along the Chippewa and Eau Claire

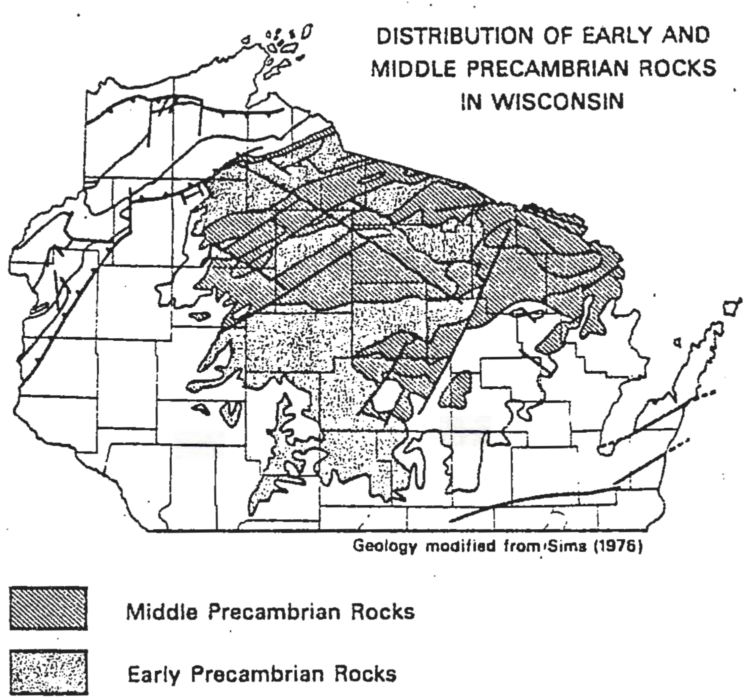

Figure 2. Map of northern Wisconsin showing distribution of Early and Middle Precambrian rocks as revised from Sims (1976). Since 1976, reconnaissance geologic mapping and availability of detailed aeromagnetic maps by Zietz, Karl and Ostrom (1978) have permitted revisions in the map by Sims, Cannon and Mudrey (1978). Major changes have been to increase the extent of Middle Precambrian units while decreasing the extent of Early Precambrian units, and to refine the location and extent of bedrock faults (after LaBerge and Mudrey, 1979).

Rivers. Cummings and Myers (1978) showed that amphibolites and gneisses in Eau Claire and Chippewa Counties had undergone two periods of metamorphism and deformation prior to being intruded by 1850 m.y. old plutons. However, structural studies of gneisses at several localities in central Wisconsin, and radiometric dating, led Maass, Medaris and Van Schmus (1977) to conclude that the gneisses in central Wisconsin are mainly of Middle Precambrian age. Thus, there may be more than one age of gneissic rocks in the region.

In Wisconsin the Lower Precambrian terrane is interrupted by younger Middle Precambrian rocks which include three main types: volcanic rocks, sedimentary rocks, and intrusive granitic rocks (Fig. 3). The volcanic rocks, which are dominant in the south, appear to be basaltic to felsic in composition, and submarine in origin. Pillows are evident in the greenschist-grade rocks, along with agglomerates and interbedded iron formations and slates. Model lead ages on galena from massive sulfide deposits in the volcanic rocks are 1,820 and 1,835 m.y. (Stacey and others, 1976). The northern part of this Middle Precambrian terrane is characterized by slates and iron formations, which rest unconformably on Lower Precambrian basement in the Gogebic Range.

The volcanic-sedimentary sequence is intruded by Middle Precambrian granitic rocks, ranging in age from about 1,850 to 1,765 m.y. (Van Schmus, 1976 and in press).

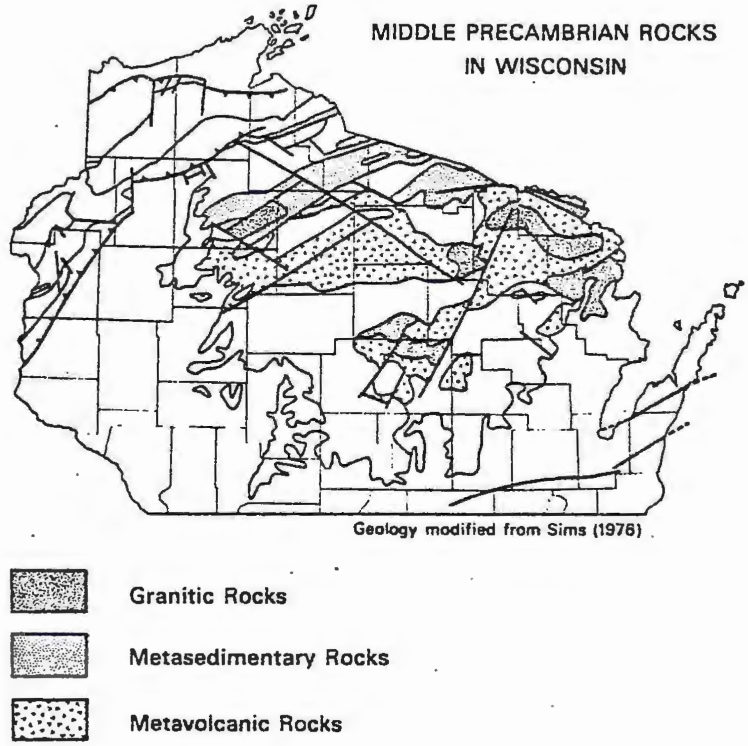

Figure 3. Map of northern Wisconsin showing distribution of various lithologies in the Middle Precambrian as modified from Sims (1976). Since 1976, reconnaissance geologic mapping and availability of detailed aeromagnetic maps by Zietz, Karl and Ostrom (1978) have permitted revisions to the map by Sims, Cannon and Mudrey (1978). Major changes have been to increase the extent of volcanic rocks in the southwestern part of the map, and to redefine Early Precambrian gneissic areas as foliated Middle Precambrian granites. (After LaBerge and Mudrey, 1979).

The older plutons, consisting of granites and tonalites, are mainly syntectonic, and many show a pervasive cataclastic foliation (LaBerge and Myers, 1976; LaBerge, 1977). The older pulse of plutonic activity is dated by Van Schmus (in press) at 1,840-1,820 m.y. ago. Medium-grained granitic to tonalitic plutons were emplaced throughout north-central Wisconsin between 1840 and 1830 m.y. ago (Maass, Medaris and Van Schmus, 1980). This activity was followed by the emplacement of finer-grained granitic to tonalitic plutons along the southern margin of this area between 1830 and 1820 m.y. ago. Penokean orogenic activity and deformation had ended prior to the emplacement of 1760 m.y. old granites and rhyolites in southern Wisconsin. These younger rocks, consisting of potassic granites and associated rhyolitic volcanic rocks, are thus post-tectonic and generally are little deformed.

The Upper Precambrian consists of thick successions of flood basalts, cogenetic gabbroic intrusive rocks, and isolated quartzite units in northern Wisconsin, and the Wolf River batholith of east-central Wisconsin. Chase and Gilmer (1973) proposed that an aborted continental rift occurred during the Late Precambrian along the Mid-Continent Gravity High. A number of unmetamorphosed diabase dikes of presumed Keweenawan age in the present study area appears to represent the youngest Precambrian event.

Marathon County Geology

Introduction

Marathon County is situated near the southern margin of the exposed Precambrian shield. The bedrock is predominantly Precambrian igneous and metamorphic rocks with a few scattered outliers of Paleozoic sandstone that unconformably overlie the Precambrian rocks (Fig. 4). Lower Precambrian (?) gneisses and Middle Precambrian volcanic rocks are intruded by numerous syn- to post-tectonic Middle Precambrian plutons ranging in composition from quartz diorite to granite (LaBerge, 1980). The volcanic rocks range in composition from basalt to rhyolite and occur as isolated pendants and blocks in the plutonic rocks. Major zones of cataclasis separate gneissic rocks from the greenschist facies Middle Precambrian volcanic-plutonic complex.

Early (?) Precambrian

Gneisses and Schists

In Marathon County the gneissic rocks are poorly exposed and consist mainly of large frost-heaved blocks and widely scattered outcrops. The rocks are medium- to coarse-grained quartzofeldspathic biotite- and hornblende-bearing gneisses, schists and migmatites which underlie northwestern Marathon County and occur as isolated blocks along the southern edge of the county. The gneisses range in composition from quartz

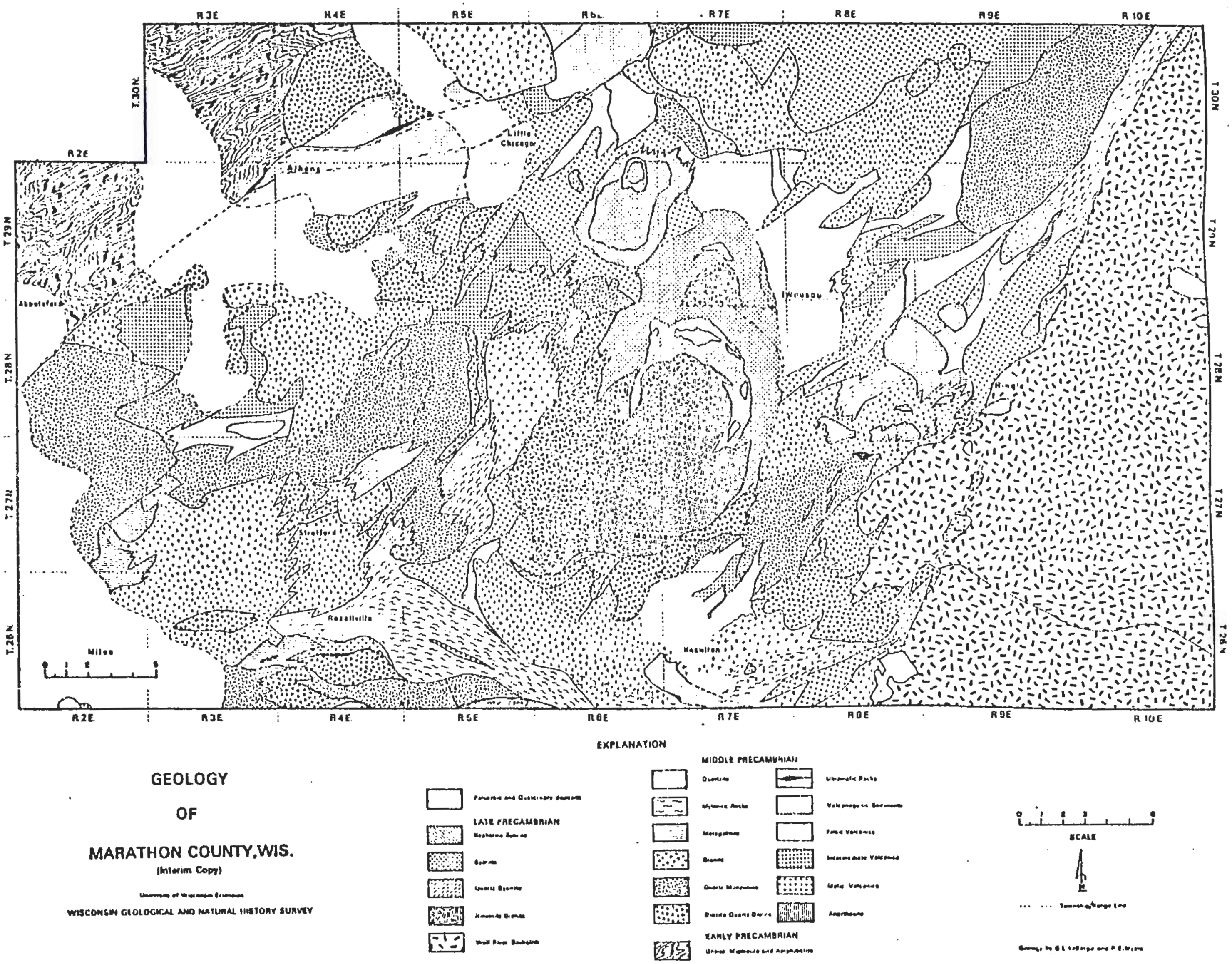

Figure 4. Geological map of Marathon County showing the major lithologic units (from LaBerge, 1978).

diorite to granite and have a conspicuous foliation and lineation. Biotite or hornblende or both comprise 15-40 percent of the rock and some phases are garnetiferous. The common occurrence of hornblende, and locally garnet, suggests that they have been metamorphosed to amphibolite facies.

The gneissic rocks have a distinctive aeromagnetic pattern of gently curving anomalies, compared with a blotchy pattern of magnetic highs and lows in the remainder of Marathon County (LaBerge, 1980). The Bouguer Anomaly Gravity Map of Ervin and Hammer (1974) shows the gneisses as a distinct area of zero to minus 40 milligals, compared with minus 40 to minus 90 milligals for the remaining rocks in the county.

Middle Precambrian

Metavolcanic Rocks

Volcanic rocks occur as xenoliths and pendants in intrusive rocks and as relatively continuous areas in northern and eastern Marathon County. They range in composition from basalt to rhyolite and exhibit a wide variety of textures and primary structures, including pillow lavas, massive flows, flow breccias, welded tuffs, tuffs, and volcanogenic sediments. The rocks have undergone greenschist facies metamorphism and local cataclasis. Primary volcanic textures and structures are locally well preserved; elsewhere metamorphism has partially to completely obliterated volcanic features. The volcanic sequence in Marathon County has been extensively disrupted by faulting and intrusion, forming isolated blocks surrounded by plutonic rocks (LaBerge, 1980). U/Pb age determinations on zircons in rhyolite on the east edge of Wausau indicate that volcanic rocks in this area are 1900 m.y. old (Van Schmus and others, 1975). No other age determinations of volcanic rocks in Marathon County have yet been reported, although LaBerge (1980) assumes the other volcanic rocks to be part of the same period of volcanism.

Sedimentary Rocks

Mapping by LaBerge and Myers indicates a limited distribution of metasediments in Marathon County which are extensively and complexly interbedded with volcanic rocks. The rocks consist primarily of graywackes and slates or argillites and are widely distributed throughout the county. However, no large continuous areas of sediments are exposed.

Intrusive Rocks

The volcanic rocks have been intruded by more than twenty stock-like plutons in Marathon County. Most of the plutons range in composition from quartz diorite to granite, with several gabbroic intrusions also present. The intrusive units appear to be discordant with the host rocks and contact metamorphic effects are generally meagre. In the present study area both the volcanic-sedimentary sequence and the gneisses have been intruded by granitic plutons.

The Middle Precambrian volcanic-plutonic portion of Marathon County is situated on one of the major gravity lows in the state (up to minus 90 milligals) (Ervin and Hammer, 1974). The gravity low is significantly greater than that over the gneissic area described above. This may indicate that the area is underlain mainly by granitic rocks. The general gravity low suggests that the volcanic pendants are relatively shallow features in the granitic rocks (LaBerge, 1980). The aeromagnetic map of the area (Zietz and others, 1978) is consistent with this interpretation. The granites have a low, flat magnetic expression whereas the gabbros and volcanics produce magnetic highs. This is the reverse of the magnetic pattern described elsewhere in northern Wisconsin by Mudrey and Karl (1978).

Only a few radiometric ages are available from plutonic rocks in Marathon County. Van Schmus and others (1975) report a U/Pb age of 1850 m.y. on zircons from a quartz monzonite in northeastern Marathon County.

Late Precambrian

In Marathon County the Late Precambrian is represented by widely distributed igneous rocks, including quartz monzonites, granites, syenites, and several types of diabase dikes. The quartz monzonites and granites are part of the large Wolf River Batholith which underlies at least 3500 square kilometers in eastern Marathon County and adjoining parts of northeastern Wisconsin. U/Pb age dates on zircons indicate the batholith is 1500 m.y. old (Van Schmus and others, 1975). Two elliptical, concentrically zoned alkalic plutons intruded the Middle Precambrian volcanic-plutonic complex just west of Wausau (Myers, 1976). These plutons are about 1500 m.y. old and are chemically related to the Wolf River Batholith (Van Schmus and others, 1975). Undeformed and unmetamorphosed diabase dikes are also present in Marathon County. Although the relative age of the dikes are not known, they may represent the youngest igneous rocks because they intrude all older rocks in the region.

Structural Geology

Marathon County is on the southern margin of the large Middle Precambrian volcanic-sedimentary basin that extends across northern Wisconsin into Minnesota and Michigan (Fig. 3). Relatively unmetamorphosed volcanic and plutonic rocks predominate in Marathon County. Major zones of cataclastic rocks appear to bound the Middle Precambrian volcanic-plutonic complex in Marathon County on all sides (Fig. 5). A zone of cataclastic

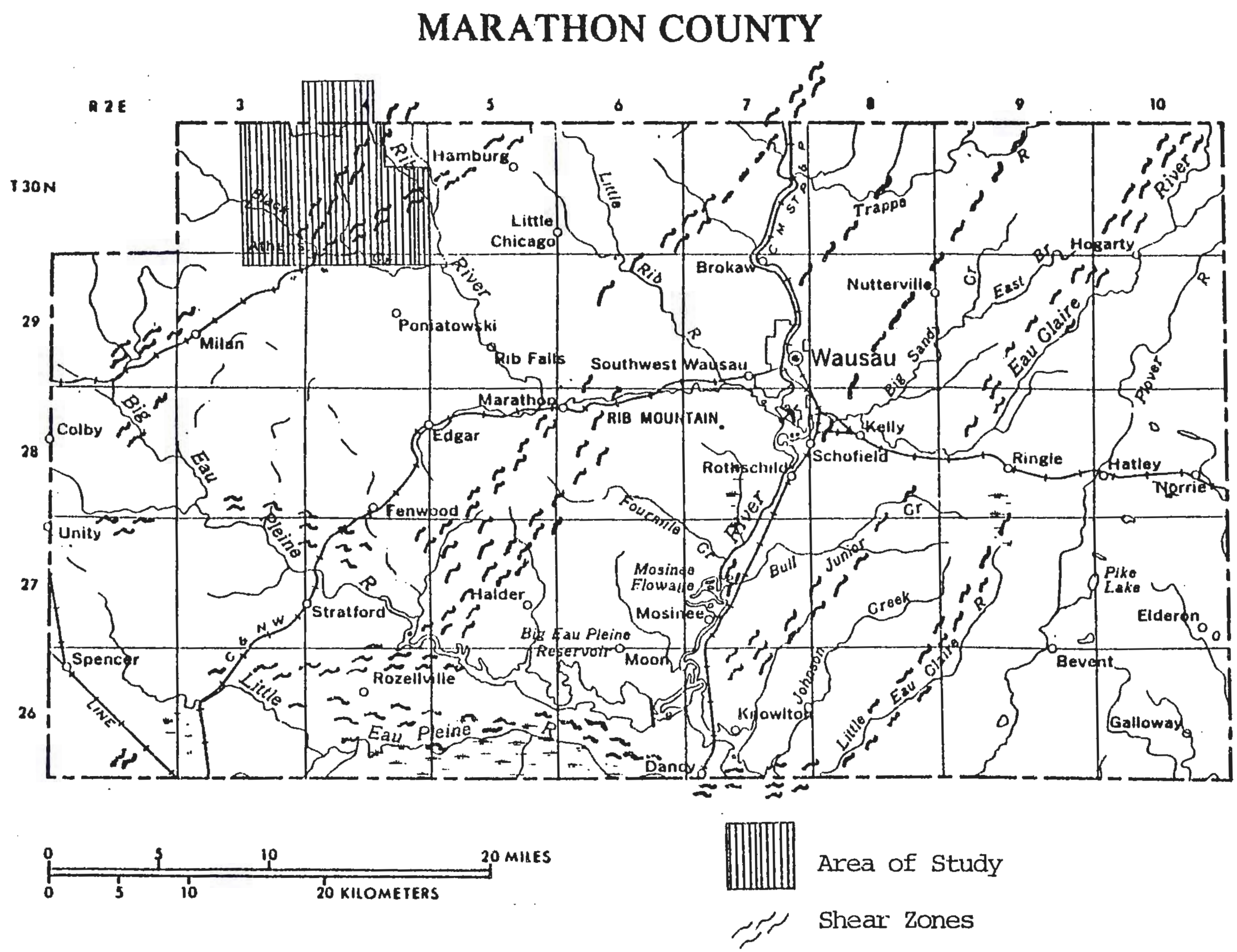

Figure 5. Marathon County Shear Zones (after LaBerge and Myers, 1976).

rocks 1-5 km wide extends from the northeast corner of the county southwest down the Eau Claire and Little Eau Claire River valleys near the south edge of the county. The Wolf River Batholith lies east of and has locally metamorphosed the deformed rocks of this zone. A similar broad zone of cataclastic rocks extends in a southwesterly direction along the northern edge of the volcanic-plutonic terrane in Marathon County. It separates gneisses, migmatites and amphibolites on the north from greenschist facies rocks to the south. The zone has been traced from near Merrill southwest through Athens to Milan (LaBerge, 1980). These two major cataclastic zones coincide with aeromagnetic and gravity lineaments, with magnetic lows and local highs parallelling the structures.

Numerous other cataclastic zones are also present within the volcanic-plutonic terrane, trending parallel to the major boundary zones. The zones are up to several kilometers wide and consist of branching and anastamosing zones of intensely deformed rocks within a broader zone of less deformed rocks. The zones cross plutonic and volcanic rocks alike, producing a wide variety of cataclastic rocks. A pervasive cataclastic foliation with a consistent regional trend (east or northeast) is present in most of the Middle Precambrian plutons in Marathon County. The lack of pervasive foliation in Upper Precambrian plutons is a major distinction between them and Middle Precambrian rocks (LaBerge, 1980).

Cambrian Sandstones

The Upper Cambrian Mount Simon Formation locally overlies the Precambrian unconformably in Marathon County. It is essentially composed of unfossiliferous, crossbedded sandstone occurring as scattered small outliers.

Quaternary Geology

The Precambrian and Cambrian rocks are overlain unconformably by unconsolidated till and alluvium of Quaternary age. Three ages of glacial drift are recognized in Marathon County. The earliest recorded glacial advance deposited the Wausau drift (LaBerge, 1971) (Fig. 6). The second advance deposited the Merrill drift which overlies the Wausau drift in the western and northern parts of the county. The last glacial advance deposited the Cary drift. Rivers throughout the area have cut through the drift to expose the underlying Precambrian and Cambrian bedrock.

Previous Works

The earliest geological reconnaissance into the central part of Wisconsin was made in 1847 under the direction of the United States Treasury Department.

MARATHON COUNTY

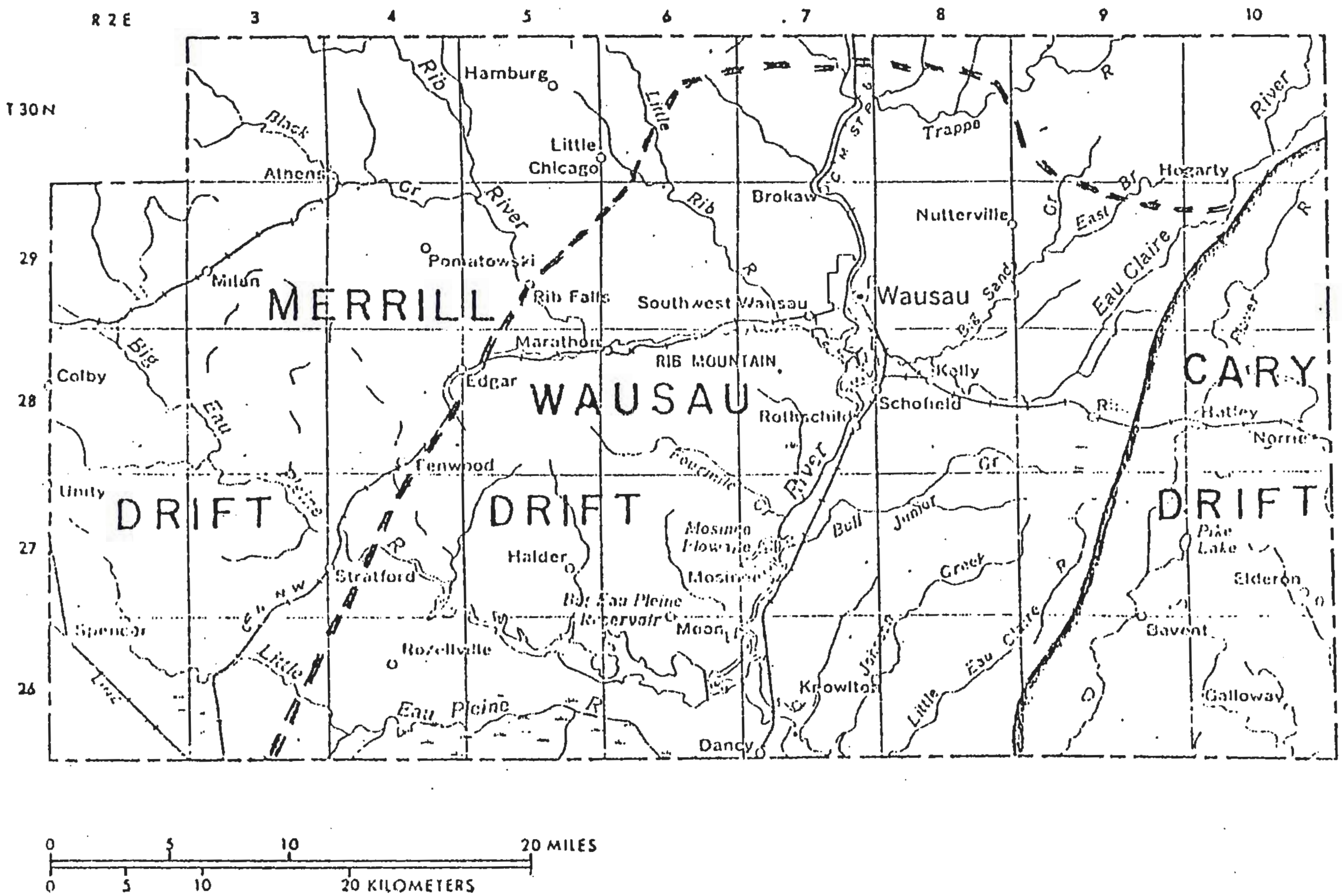

Figure 6. Map showing the approximate distribution of different till sheets in Marathon County (from LaBerge, 1976).

This general survey, which covered the territory of Wisconsin, Iowa and Minnesota, was made under the immediate supervision of Dr. D. D. Owen, whose final report was published in 1852.

In 1855 Dr. J. G. Percival, then state geologist, spent five months in making a general reconnaissance of the entire state of Wisconsin. Following the work of Dr. Percival, no further geological work was done until 19 years later, in 1874. During 1874 and 1875 R. D. Irving covered a region of about 10,000 square miles in the south-central portion of the state. Irving's area did not extend further north than Marathon County. The result of Irving's work was a general report on the Precambrian crystalline rocks.

The work of T. C. Chamberlin within the present area was principally in reference to the glacial and surficial geology. However, a short time was spent by him in the field study of this area, and his references to it are in his report on the Superficial Geology of the Upper Wisconsin Valley.

In 1907 the geology of Marathon County was studied by Samuel Weidman while working for the Wisconsin Geologic and Natural History Survey. Weidman describes the geology of Marathon County and parts of eight other counties, commenting on the topography and geography. His work presented the first comprehensive study of the Precambrian and glacial geology of Marathon County.

Weidman subdivided the Precambrian rocks into the following categories: 1) the Basal group, 2) the Lower Sedimentary series, 3) the Igneous Intrusives, and 4) the Upper Sedimentary series (see Table 1).

An early publication dealing with the relationship of structural factors to the origin of nepheline deposits in the Wausau area was filed as a report with the state survey by Emmons and Snyder (1944).

F. G. Snyder (1947) related feldspar orientation to megascopic primary structural trends in the rocks of the Wausau section of the Middle Precambrian volcanic-plutonic complex. Snyder's study includes a resume of methods of structural analysis of petrofabrics and structural data collected by Emmons and Snyder in 1944.

Extensive studies of Marathon County were begun in 1969 to produce an updated geologic map of the county and to determine the structural and age relations of the rocks (Weiss and LaBerge, 1969). Fourteen man-summers of field mapping by G. L. LaBerge and P. E. Myers led to new interpretations and a revised map of the geology of Marathon County (Fig. 4). LaBerge and Myers found a complex distribution of rock types cut by major east- and northeast-trending zones of cataclasis, not recognized in previous studies. The work undertaken by LaBerge and Myers provided the first regional synthesis of the geology of Marathon County and provides a framework for more detailed studies in the region.

Age	Weidman (1907)	Snyder (1947)	LaBerge (1980)
Paleozoic			Scattered Upper Cambrian Sandstone Outliers
Late Precambrian		Granites and Differentiates	Diabase Dikes (1200 m.y. old?) Quartz Porphyry Plugs Wolf River Batholith (1500 m.y. old)
Middle Precambrian		Rhyolite (?) Argillite and Graywacke interbedded with Rhyolite, Tuff and Agglomerate	Emplacement of Post-tectonic Plutons (1765 m.y. old) Emplacement of Synorogenic Plutons (1850 m.y. old) Major Faulting in central Wisconsin Volcanic-sedimentary Sequence (1900 m.y. old) Erosion of older sequence-?-? Metamorphism to Amphibolite Facies Early Volcanic-sedimentary Sequence
Early Precambrian	Upper Sedimentary Series Igneous Intrusives Lower Sedimentary Series Basal Group: schists and gneisses	Rib Hill Quartzite Greenstone Argillite, Slate Graywacke Granite (?), Schist Gneiss, Volcanics	Granite Intrusion Gneisses, Migmatites, Amphibolites

Table 1. Comparison of Wisconsin Geologic Columns after S. Weidman (1907), F. Snyder (1947), and G. LaBerge (1980).

A recent study which concerned itself with the structure of Marathon County was prepared by Steckley (1970). The results of joint and microfracture fabric analyses established possible principal stress directions for ten stations at selected outcrops in the county. Both petrofabric analyses and optical diffraction techniques were applied to field data to infer the stress directions.

Other recent studies in central and northern Wisconsin which have provided a basis for reinterpreting the regional geology include: 1) the compilation of the Precambrian geology by Dutton and Bradley (1970); 2) work by P. E. Myers and others in Eau Claire and Chippewa Counties (1974, 1978, and 1980); 3) work by W. R. Van Schmus and others (1975 and 1977) in eastern and northeastern Wisconsin; 4) publication of a Bouguer Anomaly Gravity Map of Wisconsin (Ervin and Hammer, 1974); 5) publication of a series of aeromagnetic maps by Karl and others (1978); and 6) general reconnaissance and detailed structural studies by Maass and others (1976, 1977, and 1980).

Statement of the Thesis Problem

The purpose of this study was to analyze a section of northwest Marathon County in the Civil Townships of Halsey, Rietbrock, Johnson, Bern, Hamburg, and Rib Falls (Fig. 7). The analysis consisted of both structural and

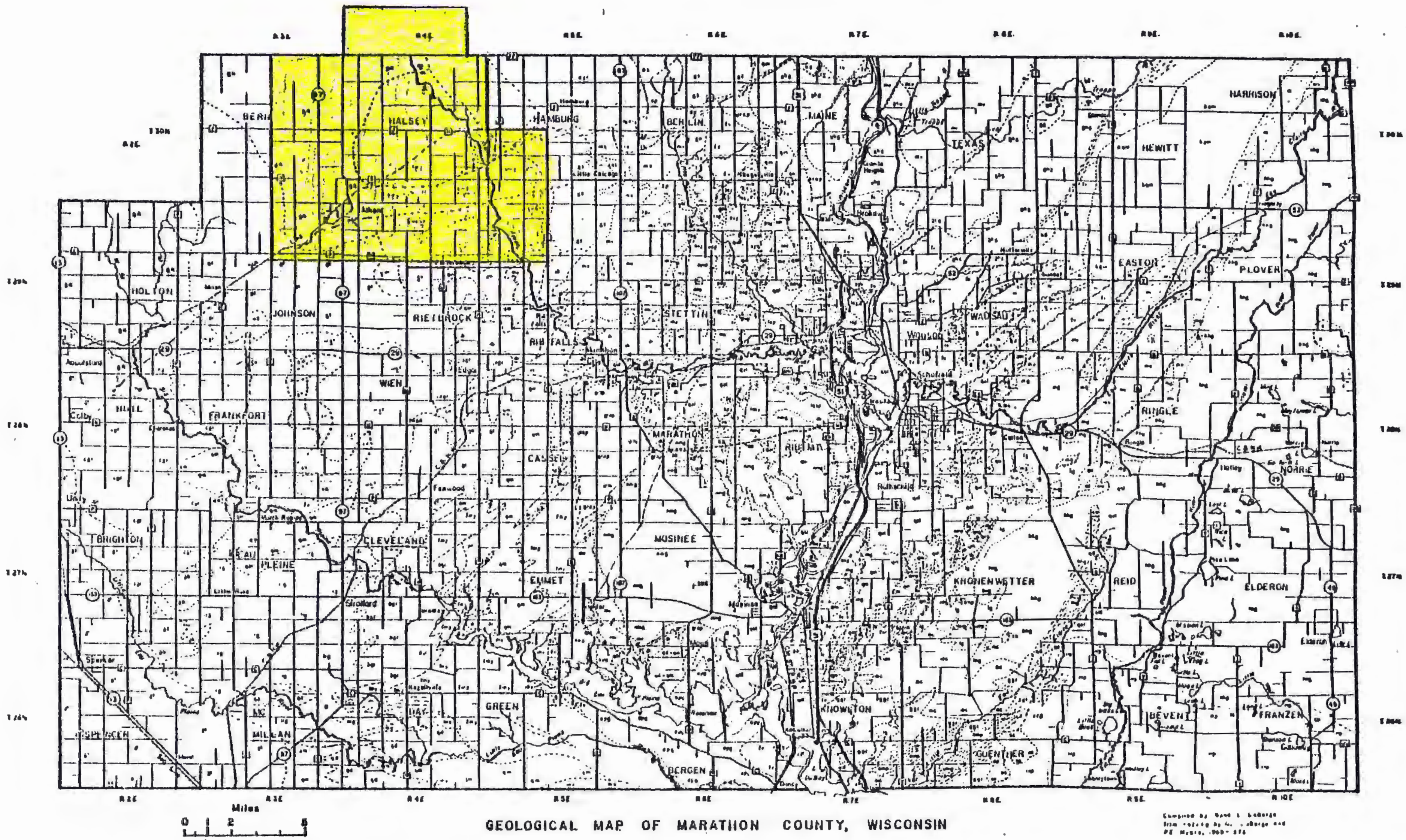

Figure 7. Geological map of Marathon County showing location of study area. Map compiled by G. LaBerge, 1978.

petrologic investigations to determine the geologic history of the study area.

Although the present study area contains extensive glacial cover, rocks mapped in the area include an extrusive region composed of basaltic to felsic metavolcanics, in addition to possible volcanogenic sediments and diabases, and a gneissic region composed of granitic gneisses, biotite gneisses, amphibolites, and migmatites. Both the extrusive and gneissic regions have been intruded by felsic plutonic rocks. The boundary between these two regions is a cataclastic zone which trends approximately N75°E through Athens, Wisconsin. The zone itself appears to have gradational boundaries, varying in width from 1-4 km, and may be anastamosing.

Thus, the present study has two objectives: 1) to present a detailed examination of these major terranes, including bulk mineralogy, grade of metamorphism, and extent of cataclasis; and 2) to investigate the structural relationships between these rock units and resolution of relict structures insofar as possible, as well as a detailed analysis of the exposed cataclastic zone.

Methods—Field Work

The field work for the present study was done during the summer of 1978. Outcrops were located by reference to previous maps (especially LaBerge and Myers, 1969-1976). Detailed attention was given to several outcrops for purposes of analyzing relationships between rock units and to provide detailed maps within the study area; these outcrops were mapped on scales of one inch to 50 feet, 20 feet, 5 feet, 2 feet, and 5 inches (see Fig. 8).

Each outcrop description included the following: location, physical dimensions and appearance, a short lithologic description including composition, size, color, presence or absence of fluxion structure and porphyroclasts or phenocrysts, foliation and lineation attitudes, and the presence or absence of other structural features such as joint systems and small scale folding and faulting.

One hundred and thirty-two rock samples were collected from the study area. Sample locations are listed by section, township and range in Appendix I.

Methods—Laboratory Work

In the laboratory 149 thin section heels were stained for potassium, using sodium cobaltnitrate, and plagioclase, using Amarand. The feldspar content was then estimated and recorded. 149 thin sections were microscopically examined. Modal analyses from point counts were obtained from 20 of the thin sections.

Over 400 penetrative structure measurements, predominantly lineations and foliations, were collected in the field. These structures were plotted on equal

MAP UNITS AND SYMBOLS

for Figure 8

- AGES INFERRED -

PRECAMBRIAN

LATE

MAFIC INTRUSIVE ROCKS

MIDDLE

FELSIC INTRUSIVE ROCKS

METAVOLCANIC ROCKS

EARLY

GNEISSES; MIGMATITE, AMPHIBOLITE-, AND BIOTITE-

73 Strike and Dip of Foliation

34 Trend and Plunge of Lineation

Area of Outcrop, Dashed where Inferred

Contact, Dashed where Inferred

Fault, Dashed where Inferred

Shear Zone

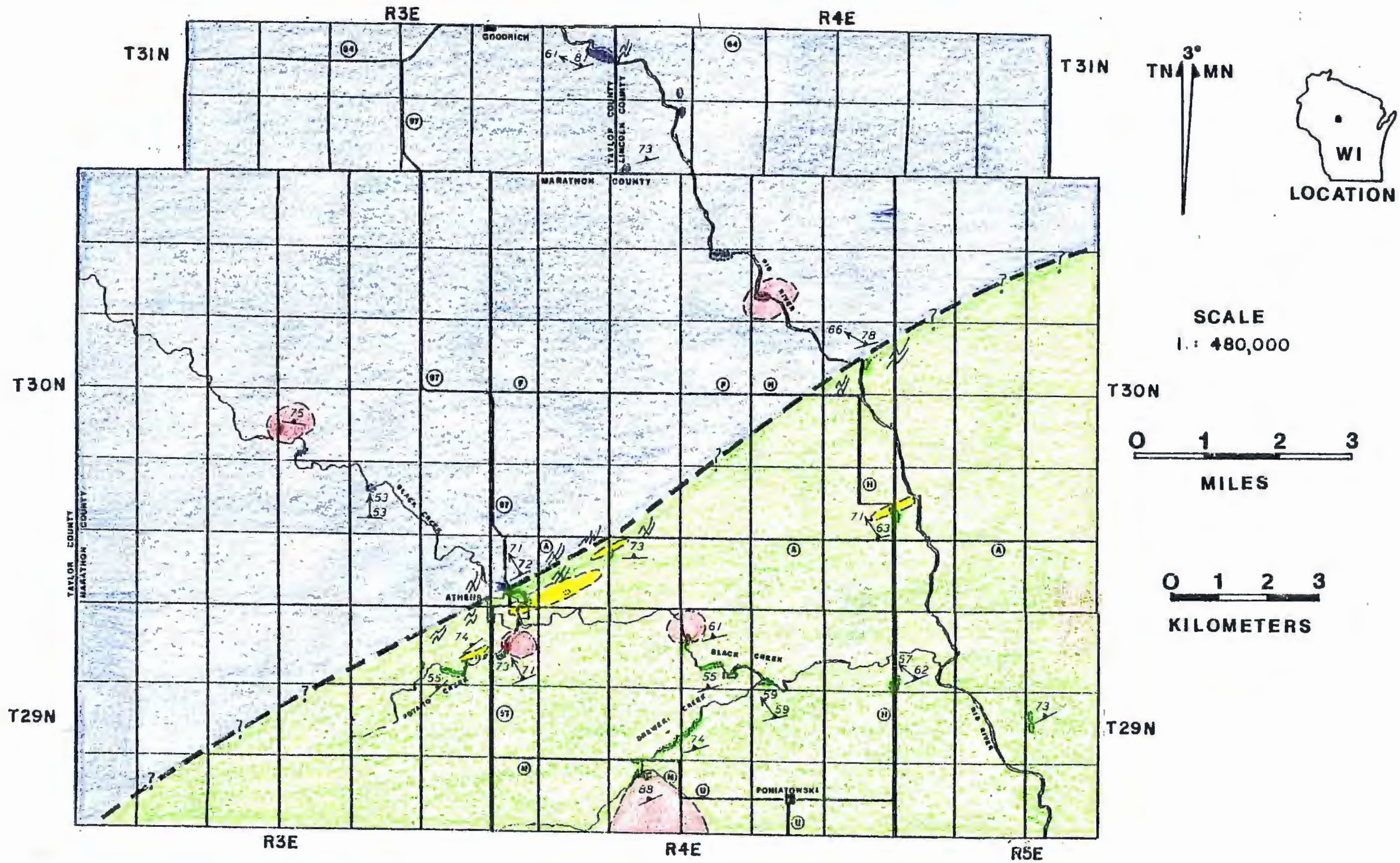

Figure 8. Geological map of thesis area.

area projections using a modified PI DI routine of Warner (1969) on a CDC 171 computer. Over 50 joint attitudes were collected in the field and poles to these structures were plotted. The data was then analyzed to ascertain the trends of the structural fabric in the study area.

Strain analysis was carried out on samples from each host unit to analyze quantitatively total cumulative strain in the rock units (Schwerdtner and others, 1977). Seven rock samples were selected and slabbed along 3 sets of orthogonal faces. At least 50 strain indicators were then measured from each face. From the measurements on each face, the two-dimensional strain was computed using the methods of Ramsay (1967) and Elliott (1970). A best fit three-dimensional strain ellipsoid was then calculated for each sample using the Pase 5 program of Siddans.

Acknowledgements

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My deep appreciation and sincere thanks are extended to Bruce W. Yeomans, to my field assistant Russell Henning, and to the people of Athens, Wisconsin, in particular Dr. John Haines and his family.

PETROLOGY

Introduction

At least 3 major rock units are recognizable from the mapping of more than 30 outcrop locations in northwestern Marathon County. These units consist of gneisses, metavolcanics, and intrusive rocks. Each unit shows varying degrees of recrystallization textures and cataclastic features. In outcrop the rocks are badly weathered and covered with a blanket of moss and lichen; as a result, recognition of distinct volcanic and cataclastic lithologies in the field is very difficult.

Classification schemes of metamorphic, cataclastic, and igneous rocks used in this paper are defined in Appendix II.

Gneisses

General Compositions and Textures

Rocks that are dominantly gneissic underlie that part of Marathon County northwest of a line trending N75°E through Athens, Wisconsin. The rocks are generally medium-grained, locally complexly folded, and contain numerous quartz and pegmatite veins. Mineralogically, the gneisses are fine- to medium-grained quartzofeldspathic rocks ranging in composition from granite to diorite. The rocks are occasionally migmatitic, as represented by samples from the Goodrich Dells area where amphibolite and granodioritic phases are involved in a variety of structures. Further, local cataclasis of granitic gneisses has produced protomylonites.

Thirty samples of gneisses within the gneissic terrane were selected for sectioning and microscopic study. Modal analyses of 12 samples are listed in Table 2. The sample locations are given in Appendix I.

Petrographic examination of granitic gneisses within the gneissic terrane revealed a fine- to medium-grained interlocking mosaic of minerals. The major minerals in the granitic gneisses are microcline, quartz and plagioclase (Figs. 9 and 10). Biotite and hornblende are usually present and may be quite abundant, ranging from 5 to 45 percent of the rock. Zircon, apatite, sphene, and magnetite are very common accessory minerals, with allanite, muscovite and garnet occurring more rarely. Alteration products of the minerals include epidote, chlorite, sericite, and opaque oxides.

Quartz monzonitic and granodioritic gneisses are fine- to medium-grained and consist mainly of plagioclase, quartz, and biotite and/or hornblende. Potassium feldspar is also present as a major constituent, but in lesser amounts than in the granitic gneisses. Epidote, sphene, and apatite are common accessory minerals and almandine garnets occur in two of the

Table 2. Modal Analyses of Gneissic Rocks

Minerals	Samples											
	ATH: 55-4b	ATH: 55-5	HAM: 6-1b	LIN: 1-1	LIN: 1-2b	LIN: 1-3b	LIN: 2-1	TAY: 1-2	TAY: 1-6a	TAY: 1-8b	TAY: 1-11	TAY: 1-13
K Feldspar	49.0	33.1	26.0	12.1	13.8	3.0	8.0	2.7	–	53.3	48.8	43.7
Plagioclase	16.2	12.7	16.7	40.9	38.6	44.6	39.9	31.7	37.5	23.3	22.3	25.2
Quartz	32.0	23.9	34.9	19.4	13.5	19.3	23.3	8.7	6.3	16.3	18.3	20.3
Hornblende	–	6.9	–	5.3	28.4	20.8	13.4	46.2	37.9	–	–	–
Biotite	2.5	16.5	21.3	18.7	–	4.9	10.1	4.1	12.3	6.2	8.7	–
Magnetite	0.3	–	–	0.4	1.4	0.4	1.1	0.8	1.0	0.2	0.7	–
Sphene	–	4.0	–	–	4.2	–	0.2	1.4	1.1	–	0.3	0.1
Epidote	–	2.0	–	2.3	–	–	–	–	1.1	0.6	0.5	3.1
Chlorite	–	–	–	–	–	2.2	2.3	3.6	1.7	–	–	4.8
Allanite	–	0.3	–	0.6	–	–	0.2	0.5	0.3	–	0.2	0.1
Apatite	–	0.2	0.3	0.1	–	0.2	0.2	0.2	0.7	–	0.2	–
Garnet	–	–	–	–	–	4.5	1.1	–	–	–	–	–
Zircon	–	0.3	–	–	–	–	–	–	–	–	–	–
Muscovite	–	–	0.7	–	–	–	–	–	–	–	–	–
Sericite	–	–	–	–	–	–	–	–	–	–	–	2.6
TOTAL %	100.0	99.9	99.9	99.8	99.9	99.9	99.8	99.9	99.9	99.9	100.0	99.9
Rock Type	Granitic Gneiss	Granitic Gneiss	Quartz Monzo-nite Gneiss	Grano-diorite Gneiss	Grano-diorite Gneiss	Grano-diorite Gneiss	Grano-diorite Gneiss	Diorite (Amph-ibolite)	Diorite (Amphib-olite)	Gran-itic Gneiss	Grani-tic Gneiss	Quartz Monzo-nite Gneiss

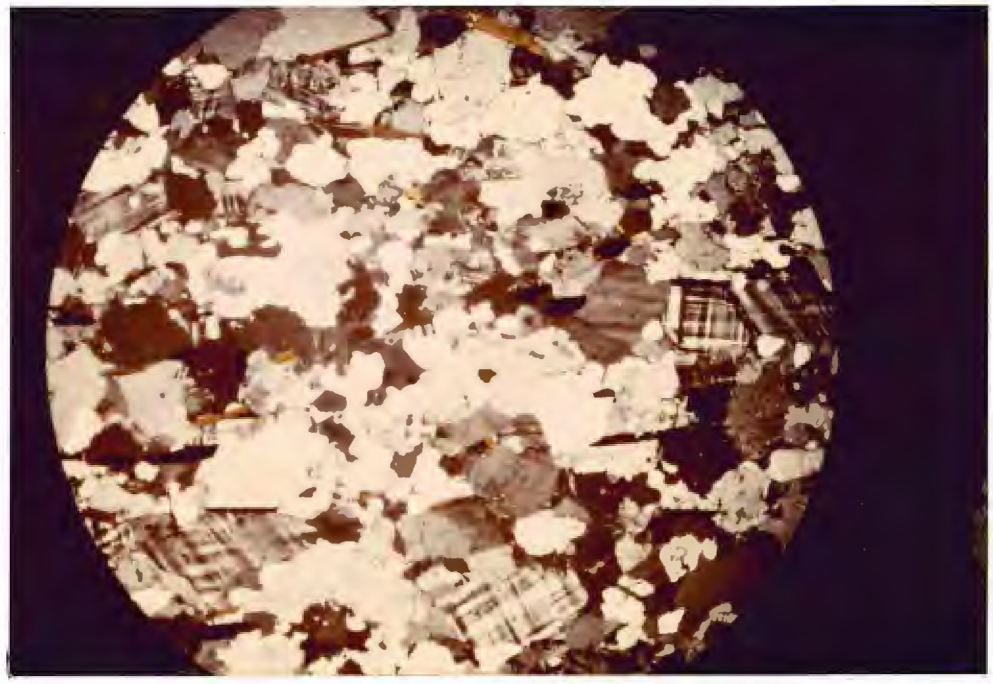


Figure 9. Photomicrograph of a granitic gneiss. Crossed polars. Sample TAY: 1-8b. Field of view 7 mm across.

Figure 10. Photomicrograph of a granitic gneiss, same view as above. Ordinary light. Field of view 7 mm across.

samples. Less common accessory minerals include allanite, chlorite, zircon, and magnetite.

Amphibolite gneisses are fine- to medium-grained and are dominantly composed of hornblende, plagioclase, and quartz. Hornblende often comprises from 25 to 45 percent of the rock (Figs. 11 and 12). Microcline and biotite are occasionally present and the latter may be quite abundant. Sphene, epidote, and magnetite are common accessory minerals, with allanite and apatite appearing in minor amounts. Common alteration products of the minerals include chlorite and sericite.

At Goodrich Dells (SE$\frac{1}{4}$, Sec. 25, T31N, R3E) the amphibolite and granodioritic gneisses are often migmatitic. In migmatites, the following parts are generally distinguished (after Mehnert, 1968): (1) the paleosome, which is the parent rock or protolith of a migmatite; and (2) the neosome, which is the newly formed rock portion. Two types of neosome are distinguishable: (a) the leucosome, containing lighter colored minerals such as quartz and feldspar, and (b) the melanosome, containing mainly dark minerals, such as biotite, hornblende, garnet, and others. The migmatites at Goodrich Dells cannot be traced back to stratigraphically equivalent but unaltered rocks, and thus the paleosome is unknown. However, Mehnert's two types of neosomes are distinguishable; amphibolite gneisses with hornblende-rich, dark bands comprise the melanosome,

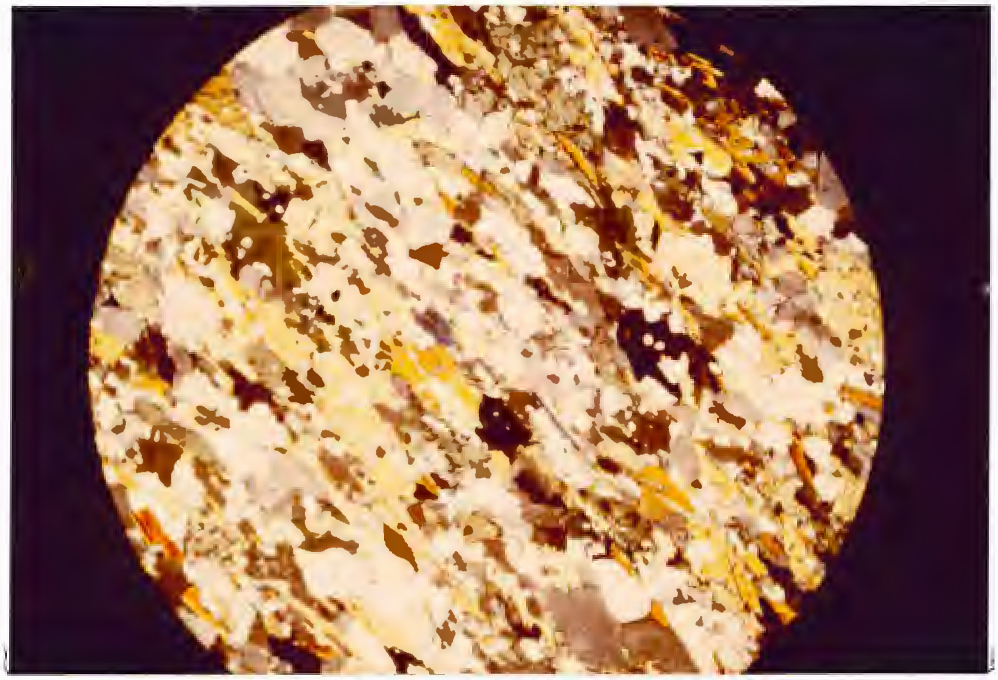


Figure 11. Photomicrograph of an amphibolite gneiss. Crossed polars. Note the poikiloblastic texture of the hornblendes. Sample TAY: 1-2. Field of view 7 mm across.

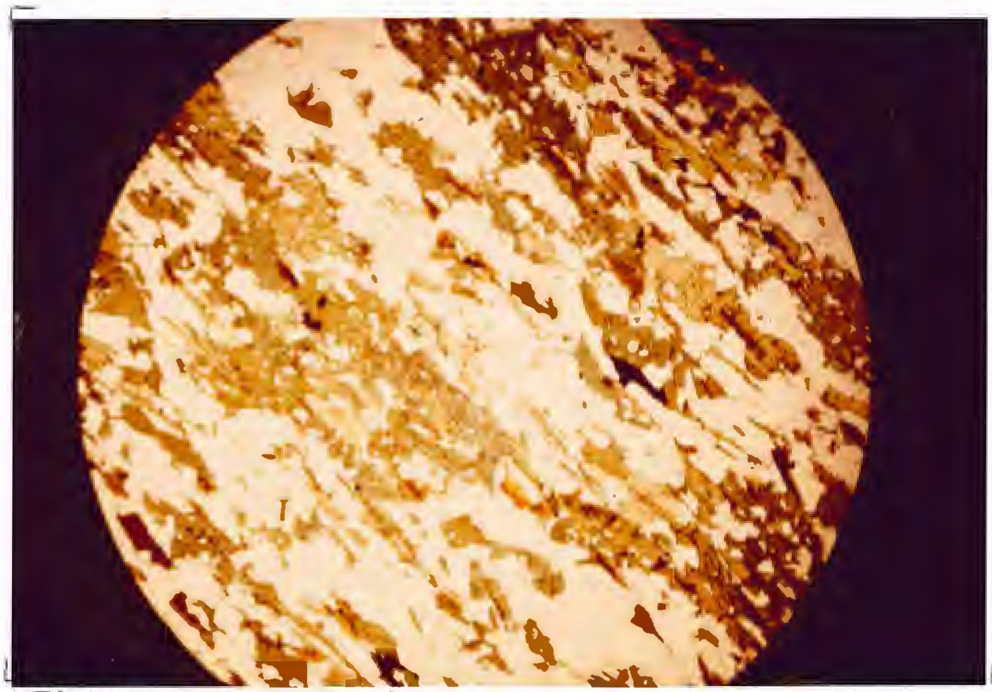


Figure 12. Photomicrograph of an amphibolite gneiss. Same view as above. Ordinary light.

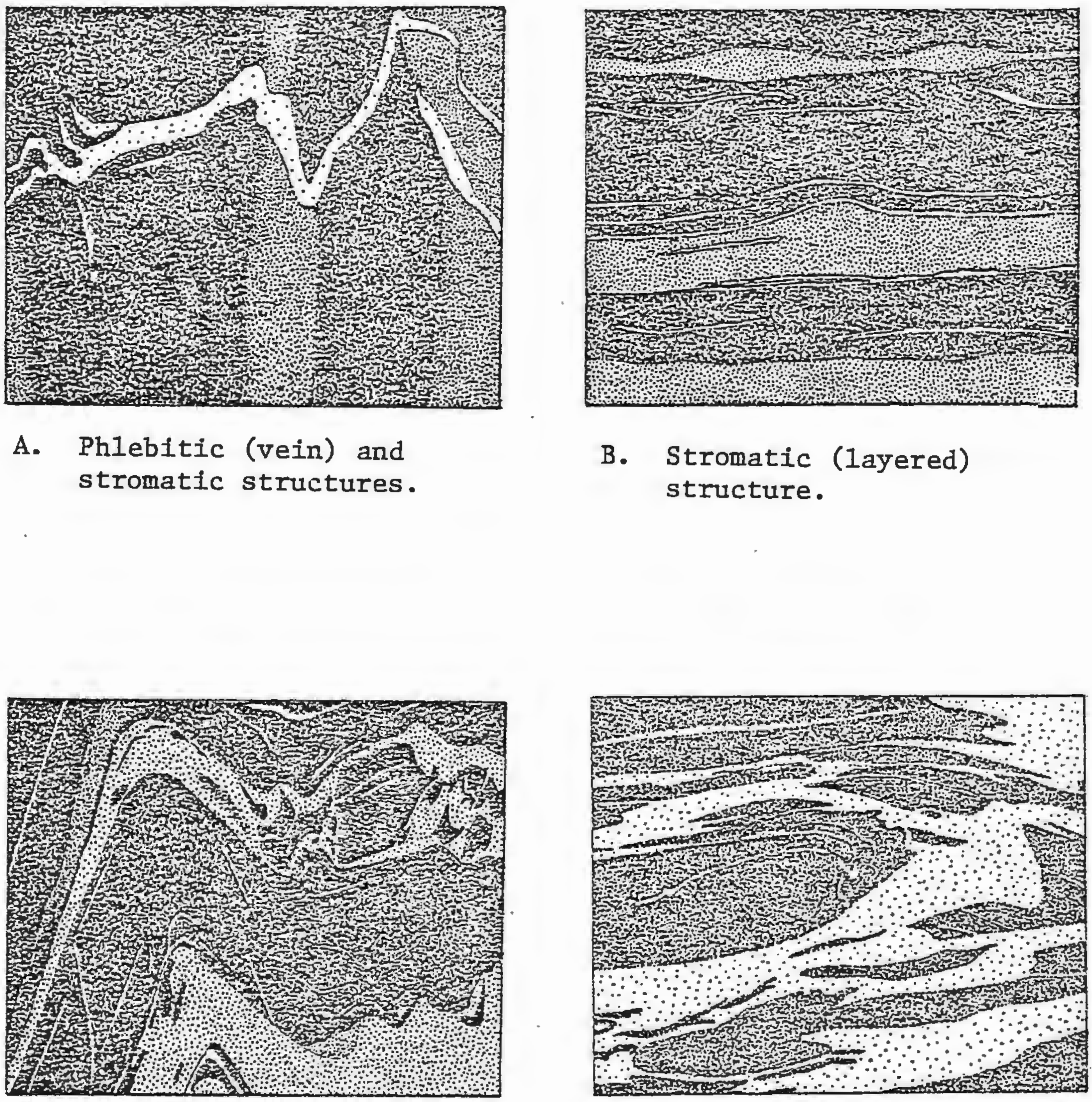
whereas granodioritic phases containing plagioclase-quartz-rich, light-colcred bands comprise the leucosome.

Texturally, the gneissic rocks are similar and exhibit well-recrystallized grain structures, polygonal and irregular grain boundaries, inequigranular textures with a common bimodality, and weak to strong foliation. The granitic and quartz monzonitic gneisses contain myrmekitic textures, exhibit varying degrees of strained grains, and commonly contain a crystalloblastic mosaic of quartz and feldspar minerals. Several samples show cataclasis with resultant mortar textures, fluxion structure and porphyroclasts. The quartz monzonitic, granodioritic and amphibolite gneisses are bimodal with respect to grain size (Figs. 13 and 14), are usually well-recrystallized with the development of straight grain boundaries, and usually both compositionally and color-banded.

The migmatites exhibit a variety of structures in the field (Fig. 15). Phlebitic structure has the rough appearance of the vein system of the human body, and has thus been referred to as veined gneiss (Mehnert, 1968). The term used is purely descriptive. Stromatic structures consist of light and dark layers generally parallel to the plane of schistosity. Schlieric structures consist of light and dark streaks of more or less elongated shape. If the streaks are exactly parallel, narrow and straight, the structure is called "banded",

Figure 13. Photomicrograph of a recrystallized bimodal granodioritic gneiss. Crossed polars. Sample LIN: 1-1. Field of view is 7 mm across.

Figure 14. Photomicrograph of a recrystallized bimodal granodioritic gneiss. Same view as above. Ordinary light.



A. Phlebitic (vein) and stromatic structures.

B. Stromatic (layered) structure.

C. Schollen (raft) and folded structures.

D. Schlieric and schollen structures.

Figure 15. Types of migmatite structures observed at Goodrich Dells in Taylor County (SE¼, Sec. 25, T31N, R3E) (after Mehnert, 1968). The darker areas are hornblende-rich and comprise the melanosome, whereas the leucosome is lighter colored and rich in quartz and feldspar.

as for instance in a banded gneiss. Schollen structure consists of angular to somewhat rounded fragments that often exhibit deformation structures due to shearing and rotational movement. The migmatites show local shearing and faulting (Fig. 16).

Mineralogy

Potassium feldspar constitutes up to 55 percent of the granitic gneisses, and is less abundant in the quartz monzonitic, granodioritic and amphibolite gneisses (Table 2). It usually appears interstitially in a crystalloblastic mosaic with quartz and plagioclase, and with myrmekitic textures in the granitic and quartz monzonitic gneisses. Much of the K-feldspar shows gridiron twinning characteristic of microcline, and is not altered to a significant degree. It is commonly anhedral to subhedral with irregular to straight grain boundaries. Inclusions of quartz, biotite, magnetite, apatite, and plagioclase are common.

Quartz is volumetrically greater than 10 percent in all of the gneissic rocks with the exception of the amphibolite gneisses (see Table 2). The grains are anhedral to subhedral and form an interlocking mosaic with the surrounding minerals except where deformation has occurred. The quartz grains often show undulosity and strain, and occasionally the development of subgrains and irregular, sutured grain boundaries. Small

Figure 16. Photograph of faulted amphibolite gneiss clast in migmatite at Goodrich Dells, Sec. 25, T31N, R3E.

anhedral grains and blebs of quartz occur as inclusions within larger grains of feldspar and hornblende. Quartz occurs as bimodal grains with the finer-sized grains occurring in the recrystallized matrix and the larger, medium-sized grains occurring with feldspars as lenses or pods (megacrysts) in the gneisses.

Plagioclase ranges from 10 to 45 percent of the gneissic rocks. It occurs both as porphyroclasts and also as a "matrix former" in the gneisses. Porphyroclastic plagioclase is usually a single grain, up to 2 mm in length. These grains occur in the granitic, quartz monzonitic and granodioritic gneisses, usually at cross-angles to the foliation, and are consistently larger than the matrix plagioclase. In most of the samples, the bimodality is defined by the presence of pods of recrystallized plagioclase, often occurring with quartz and potassium feldspar. Commonly, the minerals surrounding these pods undulate with, and help to define these lensoidal structures. In some samples both the single porphroclasts of plagioclase and the pods of quartz ± plagioclase ± K-feldspar are absent altogether, or make up only a small percentage of the rock. The matrix plagioclase is usually fine-grained, subhedral and equidimensional, occurring in a crystalloblastic mosaic with other matrix minerals. It is dominantly albite and Carlsbad twinned and may contain small inclusions of round quartz blebs, subhedral biotite, and euhedral zircon and apatite. In some of the samples the plagioclase shows heavy alteration to sericite, with twinning barely visible.

Anhedral to subhedral biotite comprises the major, and often single, mafic mineral in the granitic and quartz monzonitic gneisses. In the granodioritic and amphibolite gneisses it often occurs with hornblende (see Table 2). It occurs most often as fine-grained laths, though it may range up to 2 mm in length. When biotite and hornblende occur together they are most often intergrown. Usually the biotite is a dark-brown to a tan-brown color. Euhedral apatite and zircon are often included in the biotite grains. Epidote and allanite are often associated with biotite and alteration of biotite to chlorite and epidote occurs, though usually never to completion. Bimodality within the gneisses is further defined by the presence of two biotite sizes (Fig. 14). The larger biotites, up to 2 mm in length, occur as subhedral laths arranged in clots or megacrysts. The smaller, fine-grained biotites occur as isolated subhedral laths within the groundmass. Biotite often defines the foliation in the gneisses and has a dimensional preferred orientation.

Hornblende occurs as the major mafic mineral in the amphibolite gneisses and is often present as the major mafic mineral with biotite in the granodioritic gneisses. Usually the hornblende is a pale green to deep blue-green color and occurs as anhedral to subhedral grains up to 4 mm in length. Sphene is often present with the hornblende. Hornblende within the gneisses has a dimensional preferred orientation and, along with biotite, helps define foliation and lineation. In some of the samples hornblende approaches a poikiloblastic texture, being rich with inclusions of quartz, biotite, and plagioclase.

Almandine garnet occurs in two of the granodioritic gneisses as euhedral, poikilitic grains up to 2 mm in diameter. Quartz, plagioclase and magnetite occur as inclusions within the garnets.

Apatite and zircon are nearly ubiquitous and occur as small, isolated grains which are sometimes contained within feldspars, but more often as euhedral grains in the proximity of biotite and are often concentrated within the biotite itself.

Allanite is found in several gneisses as small, anhedral to euhedral brownish grains within or near to biotite, sphene, and plagioclase. Occasionally the allanite grains are greatly altered and alteration products include highly birefringent epidote overgrowths and muscovite. Both allanite and epidote may be contained by biotite, and epidote usually extends into surrounding biotite in symplectic intergrowths.

Cataclastic Gneisses

Cataclastic gneisses were observed at several localities in the study area: at Goodrich Dells (SE¼, Sec. 25, T31N, R3E), in the town of Athens (SW¼, Sec. 31, T30N, R4E), and in Athens County Park (SW¼, Sec. 6, T29N, R4E). The rocks at Goodrich Dells are granitic gneisses and include samples TAY: 1-11, 1-13, 1-15, and 1-16. Another granitic gneiss from the same area, TAY: 1-8, shows no deformation (see Figs. 9 and 10, and Table 2). The rocks at Goodrich Dells appear to show local progressive shearing of the granitic gneiss. The cataclastic gneisses present in the town of Athens and in Athens County Park are closely associated with deformed volcanic rocks in the area.

Mineralogically, the rocks are similar to those described previously as granitic gneisses. Texturally, the rocks contain fluxion structure, and as cataclasis appears dominant over neomineralization-recrystallization, would be classified as protomylonites (after Higgins, 1971).

The rocks consist of a coherent crush-breccia composed of megascopically visible granitic fragments that are generally lenticular and separated by gliding surfaces filled with finely ground granitic material (Fig. 17). The fragments of granitic gneiss comprise more than 50 percent of the rock.

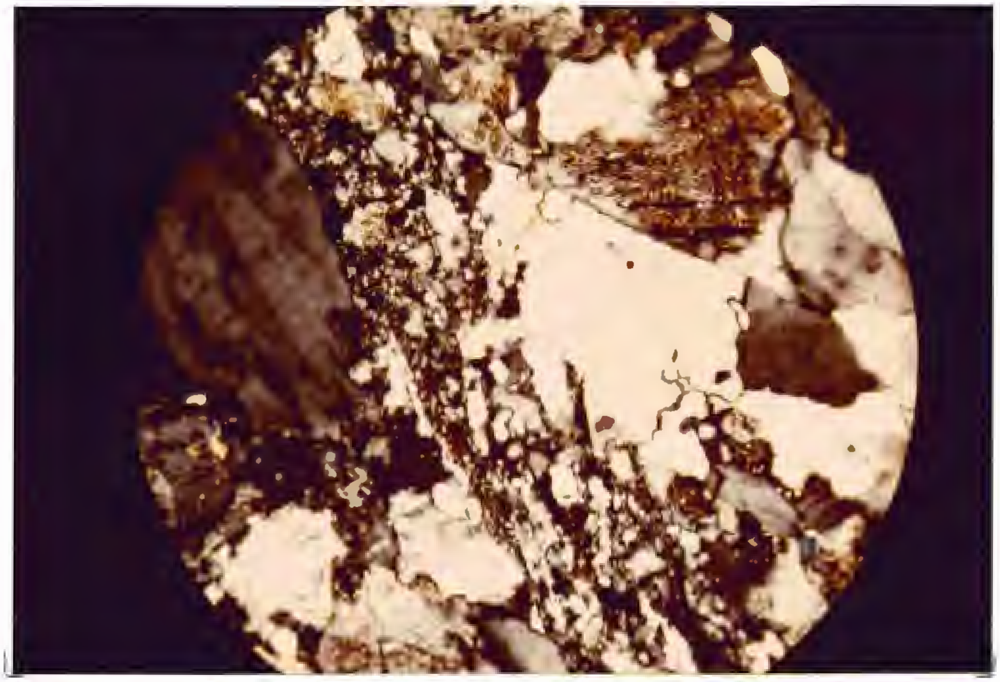


Figure 17. Photomicrograph of a cataclastic granitic gneiss. Note the mortar texture, the comminution of grains, and the alteration of feldspars. Crossed polars. Field of view is 2 mm across. Sample TAY: 1-15.

Cataclastic textures include quartz and feldspar mortar, streaks of fine-grained quartz, feldspar and biotite, and bent twin lamellae and fractures in unrecrystallized plagioclase. Quartz grains are elongated, comminuted, and severely strained. Microcline also exhibits comminution, fractures and alteration to sericite, chlorite and biotite. Large biotites have been deformed and comminuted into lens-shaped masses which are streaked out along the fluxion planes and around porphyroclasts of feldspar and quartz. The virtual disappearance of original biotite is not uncommon (see Table 2, sample TAY: 1-13). The biotites are most readily altered to chlorite, with magnetite and sphene as by-products. Biotite seldom undergoes cataclasis without chemical change. Iron is commonly expelled from biotite to form magnetite, which occurs in thin streaks along fluxion planes and helps define them. Titanium may also be expelled from biotite during cataclasis to form sphene. Recrystallized fine-grained laths of biotite formed into spindle-shaped clusters also occur. Epidote is also formed during cataclasis, and occurs as small anhedral grains with chlorite in the fine-grained mortar matrix.

Meta-volcanic Rocks

Volcanic rocks underlie that part of the study area southeast of a line trending approximately N75°E through

Athens, Wisconsin. Within the study area the volcanics range in composition from basalt to rhyolite and exhibit a variety of textures and primary structures. They include massive flows, flow breccias, tuffs, and possible volcanogenic sediments. The rocks have locally undergone low-grade metamorphism and cataclasis. Primary textures and structures are occasionally well preserved; elsewhere metamorphism has partially to completely obliterated volcanic features.

Eighty-five samples were selected for sectioning and microscopic study. The sample locations are listed in Appendix I.

Mafic Volcanic Rocks

Basaltic rocks, typically metamorphosed to lower greenschist facies, occur along Black and Drewek Creeks 4 miles southeast of Athens, and along Highway H 2 miles northeast of Ponatowski. Megascopically, the metabasalts are typically dark green to black, aphanitic, and foliated. Locally they appear to be intercalated with more felsic volcanics as indicated by recrystallized quartz-calcite pods and boudinaged felsic units (Fig. 18).

Even the freshest metabasalt contains very few primary minerals. The greenstones are largely composed of chlorite, epidote, opaques, feldspar, and quartz, indicating a greenschist facies metamorphism. Minor minerals and accessories include calcite, actinolite, sphene, pyrite, sericite, leucoxene, and iron oxides. Primary

Figure 18. Photograph of a meta-basalt. Note the foliation and boudinage structure. The boudin is a felsic, quartz-carbonate rich metavolcanic. The ruler is six inches long. Sample ATH: 53, taken along Highway H, 2 miles northeast of Ponatowski.

textures, including a fine felty groundmass with porphyritic or amygdaloidal textures, are preserved in places.

Chlorite ranges from 10 to 50 percent of the rock and occurs as fibrous aggregates (up to 0.1 mm) and amorphous masses. Epidote is observed as anhedral grains up to 0.1 mm in diameter and ranges from 10 to 30 percent of the rock. Both chlorite and epidote appear to be randomly replacing large portions of aphanitic groundmass material. They both contain a brownish amorphous material (probably iron oxides or leucoxene) which makes up a portion of the groundmass.

Plagioclase ranges from trace amounts to 30 percent of the rock and occurs as aphanitic to fine-grained, anhedral to subhedral laths. It is rarely twinned and exhibits trachytic texture. Quartz, ranging up to 10 percent of the rock, is found as anhedral equant grains up to 0.5 mm in diameter within the groundmass. It also occurs in pods with calcite as fine- to medium-grained crystals. These pods may likely be recrystallized amygdules.

Opaque oxides make up from trace amounts to 10 percent of the total rock composition. They most commonly occur as aphanitic euhedral magnetite crystals disseminated throughout the groundmass. Magnetite is typically altered to fine-grained leucoxene and iron oxides.

Accessory minerals such as calcite, actinolite, sphene, pyrite, and sericite generally make up from trace amounts to 5 percent of the total rock composition. Calcite occurs as anhedral masses replacing portions of the rock in a patchy distribution and as minute vein fillings. It also occurs as fine-grained, anhedral crystals in pods with quartz. Actinolite occurs as fine-grained, ragged, anhedral crystals largely replaced by chlorite and epidote. Sphene occurs as fine-grained rhombohedrons associated with chlorite and epidote in the groundmass. Pyrite is observed as small cubes up to 0.1 mm across, and as subhedral equant grains within the groundmass. Sericite occurs as a fine-grained, flaky secondary mineral associated with chlorite in the groundmass.

Intermediate Volcanic Rocks

Dacitic rocks occur along Drewek Creek 3 miles southeast of Athens, and along Highway H, 2 miles northeast of Ponatowski. The dacites tend to be less chloritic than the basalts, are porphyritic, and may grade into andesites with a decrease in quartz content. These rocks are light to dark green on both weathered and fresh surfaces, and are massive or foliated. The dacites consist of plagioclase, quartz, chlorite, epidote, sericite, carbonate, and opaques.

Plagioclase occurs as fine- to medium-grained, anhedral to subhedral phenocrysts. The phenocrysts, ranging from 3 to 30 percent of the rock, are commonly heavily altered to sericite, epidote, carbonate, and chlorite. Epidote has sometimes completely replaced the feldspar crystal.

Quartz phenocrysts comprise up to 20 percent of the rock and occur as fine- to medium-grained, anhedral to euhedral crystals. Occasionally volcanic quartz embayment textures are preserved. Typically the quartz phenocrysts are inclusion-free, but inclusions of plagioclase, sericite, chlorite and calcite occur.

The recrystallized, aphanitic to fine-grained groundmass (50-90 percent of the rock) is composed of plagioclase, quartz, chlorite, sericite, calcite, and opaques.

Felsic Volcanic Rocks

Rocks classed as felsic volcanics include rhyolites, rhyodacites, and quartz latites, but no attempt was made to distinguish between these in the field. In this study, they will be referred to as rhyolitic volcanics or felsic volcanics. The vast majority of volcanic rocks in the study area are felsic volcanics which exhibit a variety of textural types including lapilli tuffs, crystal tuffs, massive flows, and possible pyroclastic breccias and volcanogenic sediments.

A felsic lithic-crystal tuff unit occurs 3 miles northeast of Ponatowski. In outcrop the unit is dark green, foliated, and contains large clasts (up to 7 cm) of flattened and rotated volcanic rock fragments, in addition to phenocrysts (Fig. 19). The major constituents of the lithic-crystal tuff unit include plagioclase crystals, volcanic rock fragments, and flattened pumice fragments within an altered matrix of chlorite, opaque oxides, sericite, and carbonate (Figs. 20 and 21).

Plagioclase grains, up to 1 mm long, are the dominant crystal type recognizable and comprise up to 20 percent of the rock. The crystals are generally tabular, occasionally broken, and commonly show alteration to sericite, calcite, and chlorite.

Intermediate to felsic volcanic rock fragments typically comprise up to 40 percent of the rock and range from less than 1 mm to 15 mm in diameter and up to 70 mm in length. The fragments are angular to rounded and rotated and flattened parallel to the plane of foliation. They are generally andesitic to latitic in composition. Many are thoroughly altered to chlorite, sericite, and calcite.

Chlorite is the dominant matrix constituent composing from 15 to 40 percent of the tuff. It occurs primarily as irregular masses but may also occur as platy grains. Chlorite mostly replaces mafic crystals

Figure 19. Photograph of a lithic-crystal tuff unit. Note the volcanic rock fragments. The ruler is six inches long. Sample HAM: 1-1. The outcrop is located 3 miles northeast of Ponatowski.

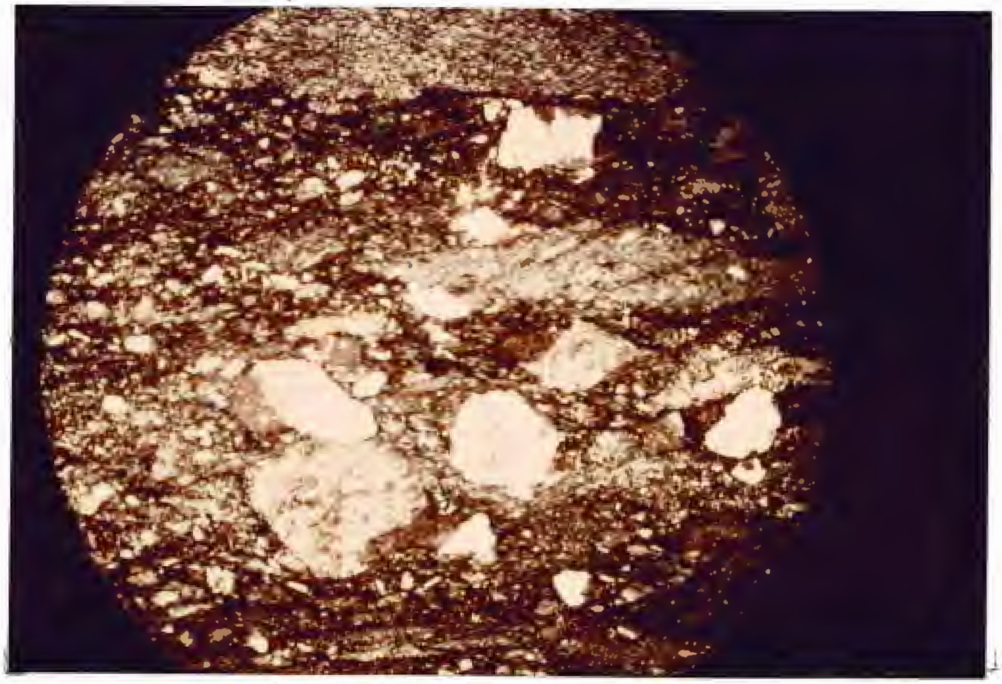


Figure 20. Photomicrograph of a lithic-crystal tuff unit. Note the volcanic rock fragments and angular phenocrysts. Crossed polars. Sample HAM: 1-1b, oriented perpendicular to foliation. Field of view is 7 mm across.

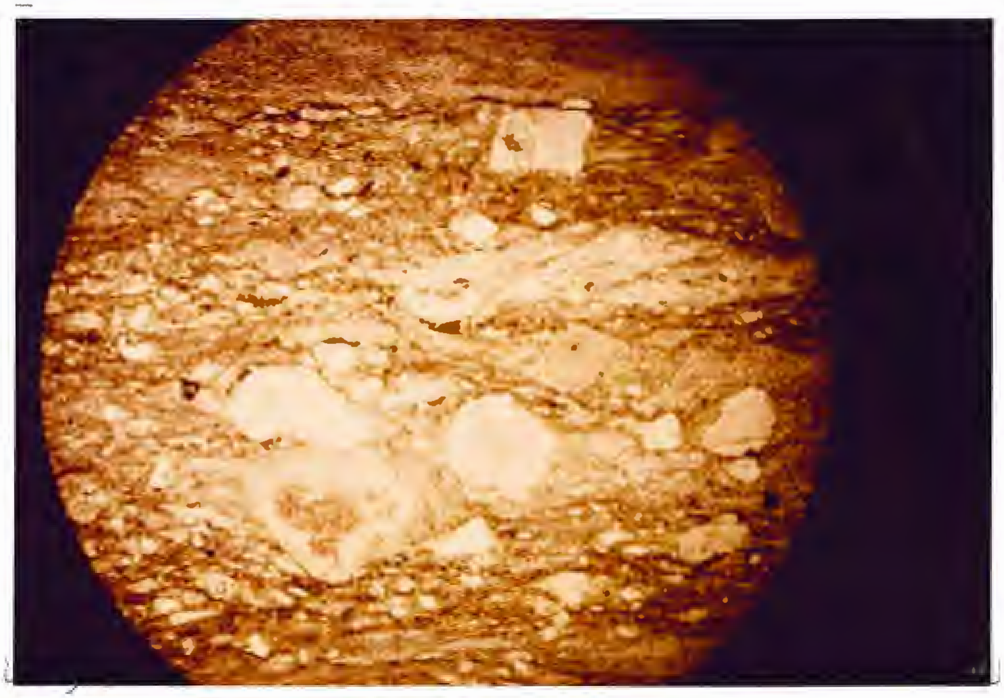


Figure 21. Photomicrograph of a lithic-crystal tuff unit. Same view as above. Ordinary light.

and occurs as the interstitial matrix between crystals and rock fragments. Calcite, epidote, and opaque oxides comprise up to 5 percent of the rock and occur with chlorite in the matrix. Calcite, up to 1 mm in size, occurs as subhedral grains replacing plagioclase and large patches within the matrix. Opaque oxides, principally magnetite, occur as anhedral to subhedral grains randomly sprinkled throughout the rock.

The minor constituents of the lapilli tuff unit occur in varying amounts and include quartz, sericite, biotite, and limonite. Quartz comprises less than 5 percent of the rock as anhedral grains up to 0.5 mm long. Sericite and biotite comprise up to 5 percent of the rock as scaly patches within the matrix.

Massive flows and recrystallized tuffaceous units varying in composition from quartz latites to rhyolites occur at several locations. Quartz latite meta-tuffaceous units occur 1 mile southwest of Athens along Potato Creek and are also exposed in a roadcut 1½ miles northeast of Athens, just south of Highway A. These rocks are inequigranular, porphyritic, and foliated. Major grain constituents include plagioclase, potassium feldspar, and quartz phenocrysts in a finer grained recrystallized groundmass of quartz, feldspar, muscovite, and biotite (Fig. 22). Minor constituents include calcite, opaques, sericite, chlorite, epidote, apatite, and allanite. Phenocrysts account for 10 to

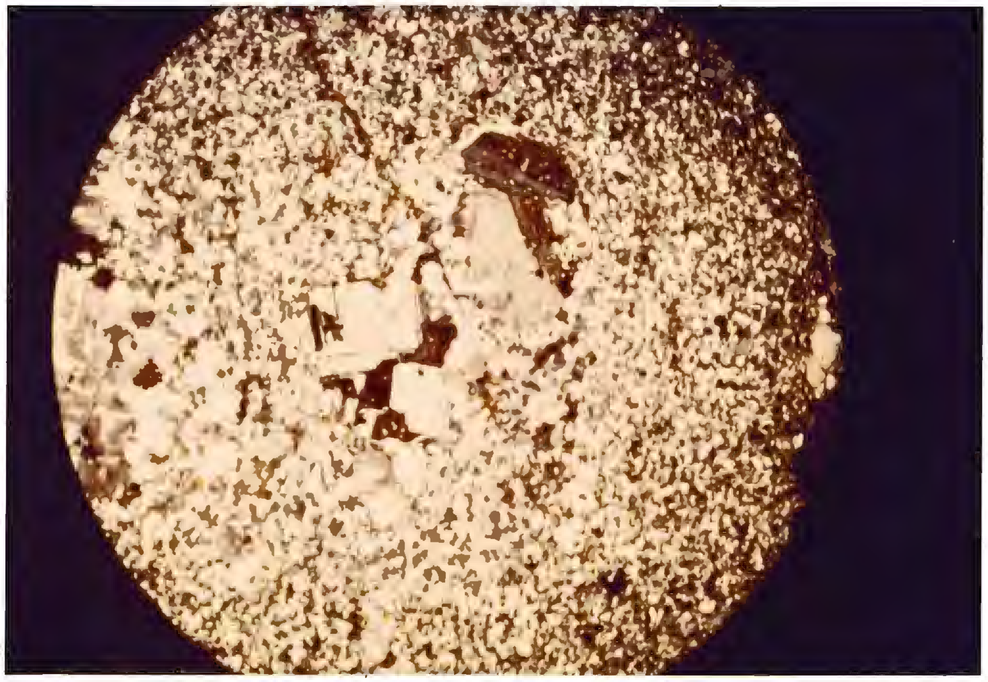


Figure 22. Photomicrograph of a meta-quartz latite. Note the glomeroporphyritic texture and recrystallized groundmass. Crossed polars. Sample ATH: 50-1b. Field of view is 7 mm.

40 percent of the rock and plagioclase accounts for 50-75 percent, and quartz about 5 percent, of the phenocrysts. Potassium feldspar generally occurs in trace amounts, but locally makes up one-fourth of the phenocrysts.

Plagioclase phenocrysts are up to 3 mm in diameter, euhedral to anhedral, and occasionally include subhedral to anhedral quartz and K-feldspar crystals. They are often extensively altered to sericite, chlorite and calcite. The plagioclase phenocrysts often occur in clumps with K-feldspar phenocrysts, producing a glomeroporphyritic texture as seen in Figure 22. Phenocrysts of quartz are generally anhedral, undulose, and range up to 2 mm in diameter. Phenocrysts of orthoclase up to 1 mm across are subhedral to anhedral. Clumps of intergrown feldspar, including some microcline, and quartz occur and may represent recrystallized amygdules. The grains are anhedral and show various stages of alteration to sericite, carbonate, chlorite, and biotite.

The groundmass of the quartz latitic rocks consists predominantly of recrystallized anhedral quartz and feldspar, fine-grained anhedral plates and subhedral laths of biotite and muscovite, anhedral epidote, and chlorite. Chlorite is also present as 0.1 mm wide veinlets. Trace amounts of magnetite, hematite, allanite, and apatite also occur in the groundmass.

Rhyodacitic and rhyolitic rocks within the field area occur as massive flow and meta-tuffaceous units. The tuffaceous units are similar to the quartz latite units already described, but plagioclase is the predominant feldspar. Within the tuffaceous rhyodacite units, plagioclase phenocrysts up to 3 mm in length are euhedral to subhedral and slightly altered to sericite, chlorite, and biotite. Subhedral quartz grains make up 5 percent of the phenocrysts and occur as subhedral crystals. Within the massive flow unit, quartz grains comprise up to 20 percent of the phenocrysts and commonly exhibit volcanic embayment textures (Figures 23 and 24). Plagioclase phenocrysts within the massive unit are extensively altered to sericite, calcite, and chlorite.

The groundmass of the rhyodacitic rocks consists of fine-grained, anhedral quartz and feldspar, 0.1 mm anhedral chlorite, sericite, and biotite, and very fine-grained dusty opaques, in addition to calcite.

Felsite volcanic rocks (or possible volcanogenic sediments) occur at several localities within the field area. The rocks are fine-grained, equigranular, and felsic in composition. Phenocrysts are typically absent (Fig. 25). Compositionally the felsites are composed of anhedral quartz and feldspar less than 0.5 mm in diameter, sericite and muscovite, chlorite, biotite, and trace amounts of apatite and magnetite. The rocks are typically foliated and recrystallized, with the micas defining the foliation. These units could also be classified as phyllites.

Deformed Volcanic Rocks

Within the metavolcanic terrane cataclastic textures are very difficult to recognize as porphyritic volcanic or metavolcanic rocks are easily confused with cataclastic rocks. Thus the extent of cataclastic deformation in volcanic rocks is quite difficult to assess.

The present literature on the interpretation of volcanic textures in a shearing environment is extremely

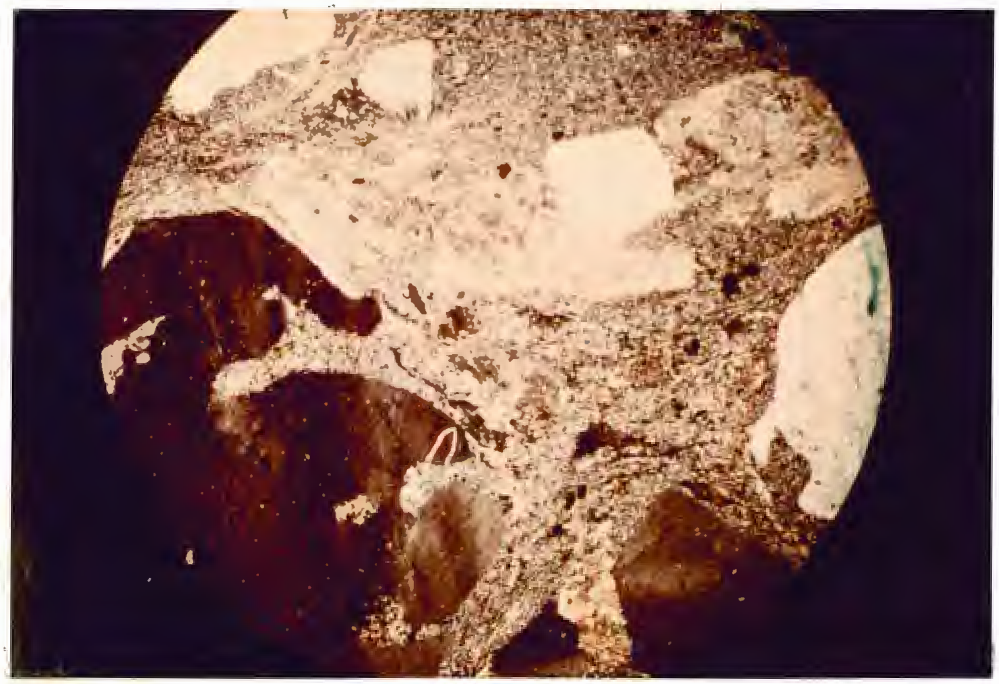


Figure 23. Photomicrograph of a rhyodacite. Note the volcanic embayment textures in the quartz, and the altered feldspars. Crossed polars. Sample ATH: 58-8. Field of view is 7 mm across.

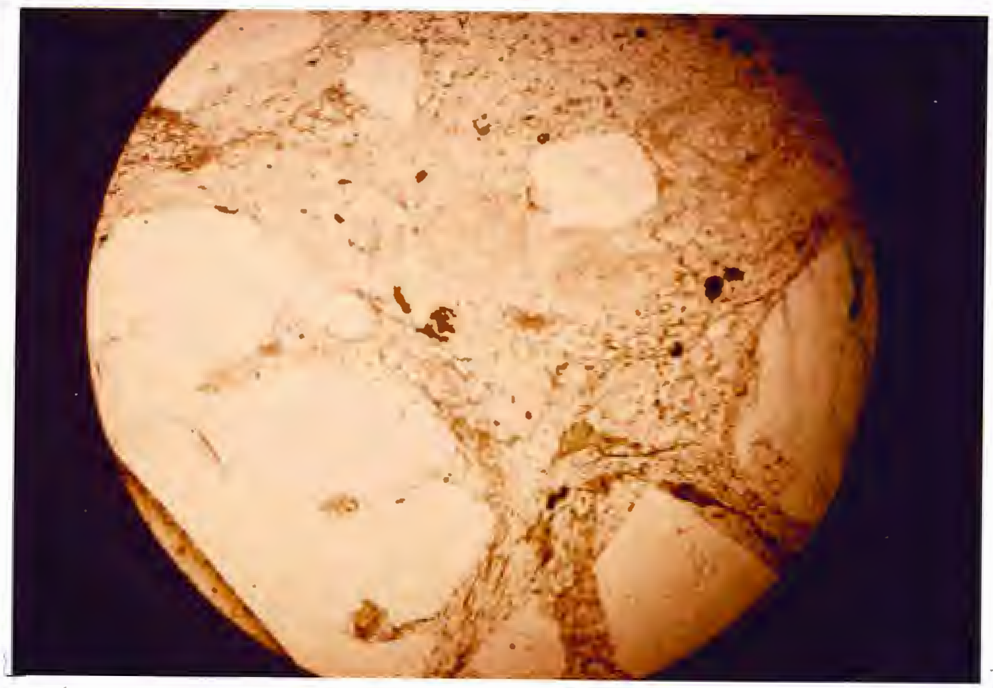


Figure 24. Photomicrograph of a rhyodacite. Note the quartz embayment textures and the flow structure in the groundmass. Same view as above. Ordinary light.

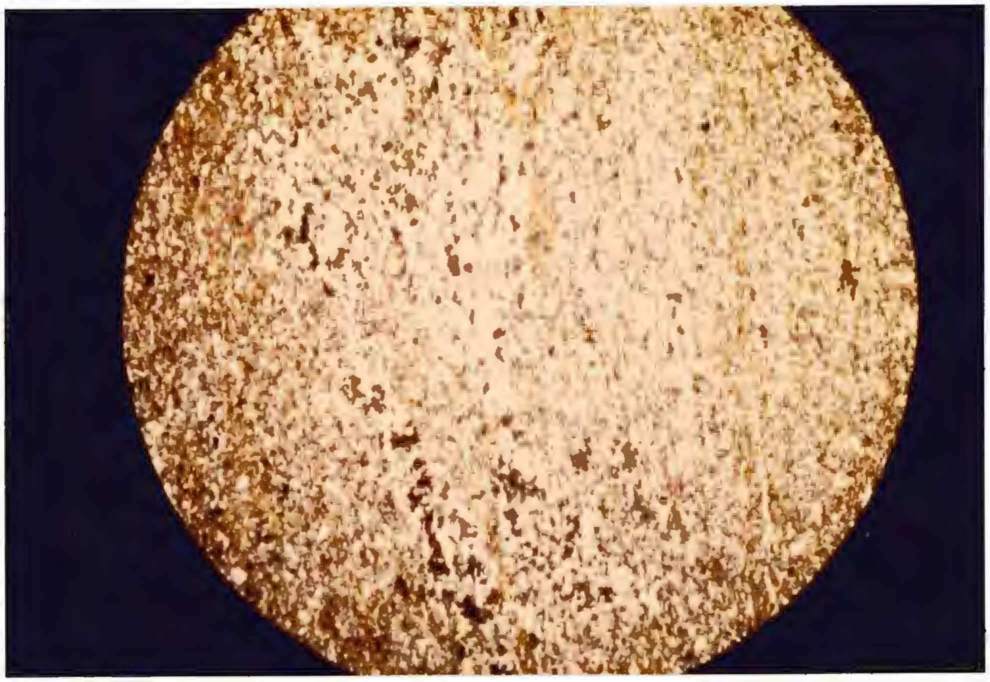


Figure 25. Photomicrograph of a felsite (?) volcanic rock. Note the fine-grained quartzo-feldspathic groundmass and absence of phenocrysts. Crossed polars. Sample ATH: 59-7. Field of view is 7 mm across.

meagre. However, Higgins (1971) states that cataclastic rocks are commonly recognized by the presence of porphyroclasts and streaking or other visible fluxion structure. One of Higgins' criteria for the recognition of cataclastic rocks is that porphyroclasts tend to be rounded, whereas euhedral or subhedral shapes are more common for phenocrysts in volcanic and metavolcanic rocks. He stresses that this criteria should be used with caution as euhedral and subhedral porphyroclasts are not unknown, and rounded phenocrysts do occur in some volcanic and metavolcanic rocks, particularly in tuffaceous rocks and welded tuffs. Further, round or nearly round porphyroblasts are also known. Another criterion Higgins uses in distinguishing porphyroclasts from phenocrysts and porphyroblasts is mineralogy. During cataclasis quartz deforms more readily than feldspars and most porphyroclasts are feldspars. Porphyroclasts of quartz, Higgins states, are rare in cataclastic rocks, but quartz phenocrysts are fairly common in volcanic, metavolcanic, and igneous intrusive rocks.

The metavolcanic rocks in the present study area are locally cataclastic. At one locality 3 miles east of Athens along Black Creek, a granodiorite intrudes a rhyodacite. In thin section both units show cataclastic textures near and along the contact between the units (Fig. 26). Within the volcanic unit plagioclase phenocrysts have been sheared and microfaulted (Fig. 27) and the recrystallized groundmass also shows deformation (Fig. 28).

Most of the deformed volcanic rocks are strongly foliated due to the extensive development of layer silicates. The felsic volcanic rocks tend to have a sericitic-muscovite groundmass, whereas intermediate and mafic volcanic rocks tend to have chloritic groundmasses. In the metavolcanic rocks the strain caused by shearing stresses may have been taken up by flowage and recrystallization of the matrix, leaving relatively

Figure 26. Photomicrograph of cataclasis along the contact between a granodiorite and a rhyodacite. Note the strained quartz grains and irregular quartz grain boundaries. Crossed polars. Sample ATH: 59-2. Field of view 7 mm.

Figure 27. Photomicrograph of a micro-faulted plagioclase phenocryst in a rhyodacite. Crossed polars. Sample ATH: 59-2. Field of view is 7 mm across.

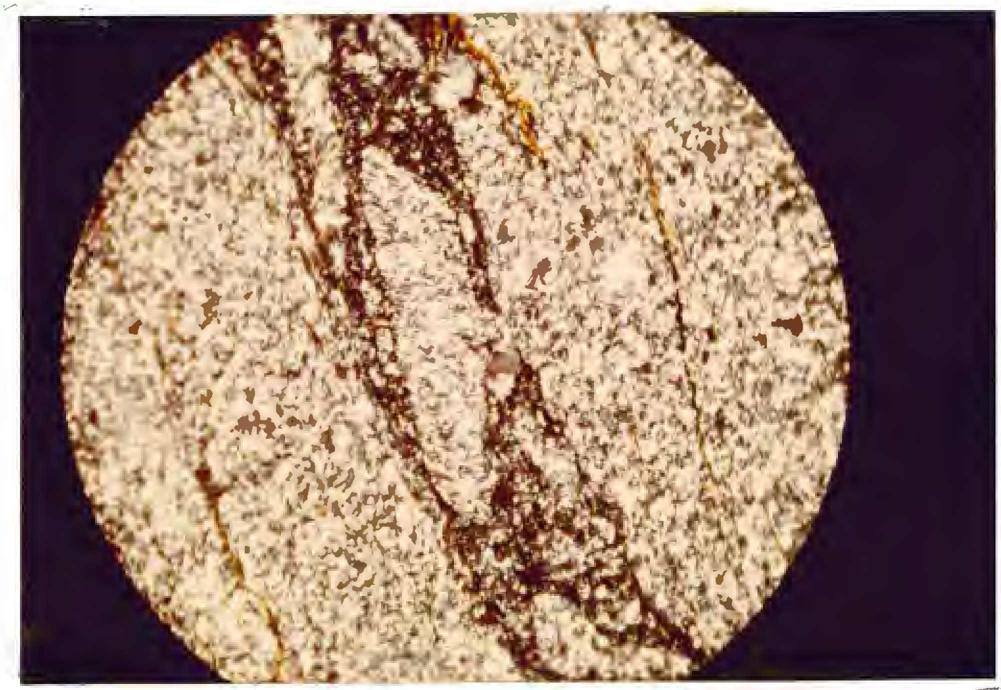


Figure 28. Photomicrograph of cataclastic deformation of the volcanic groundmass in a rhyodacite unit. Crossed polars. Sample ATH: 59-2. Field of view is 2 mm across.

euhedral phenocrysts in a highly foliated micaceous matrix (Figs. 29 and 30). Deformation of rhyolitic tuffs may result in flattening and/or elongation of the volcanic fragments; this texture could be confused with primary layering of the tuffaceous unit. In some of the felsic volcanic units the phenocrysts show rotation into the plane of foliation (cataclastic deformation or primary flow structure?) and are boudinaged. Most often the megacrysts are partially to completely surrounded and delineated by micaceous secondary minerals as can be seen in Figure 29.

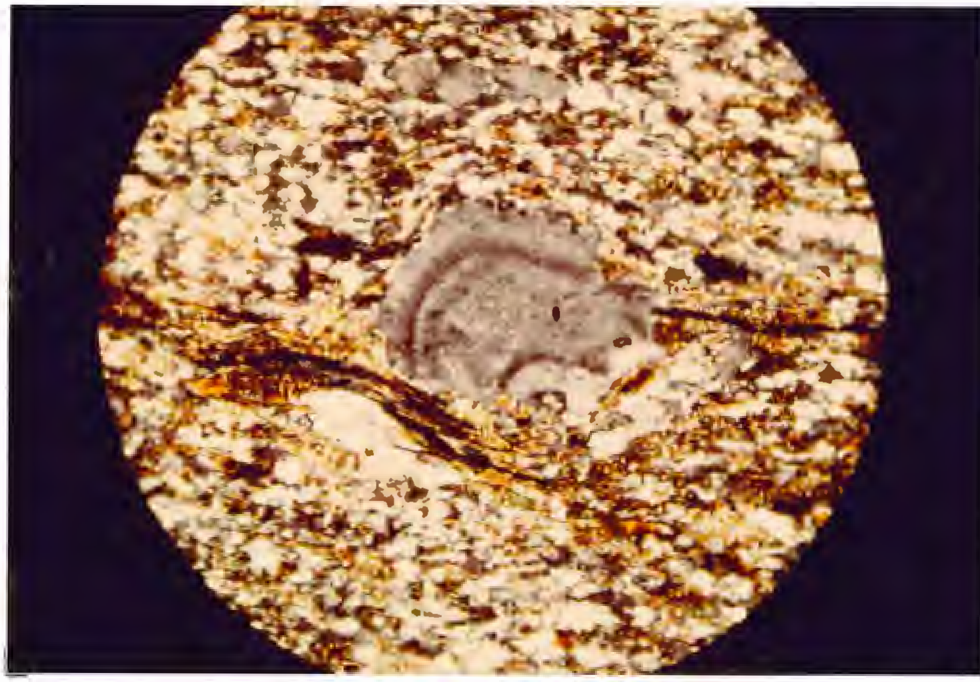


Figure 29. Photomicrograph of a cataclastic meta-rhyodacite. Note the relatively euhedral, broken and zoned plagioclase phenocryst surrounded by secondary micaceous minerals. Crossed polars. Sample ATH: 51-13. Field of view is 2 mm across.

Figure 30. Photomicrograph of a porphyritic meta-dacite. Note the undulose quartz phenocryst and the subhedral plagioclase phenocrysts. Crossed polars. Sample ATH: 53-1. Field of view 7 mm.

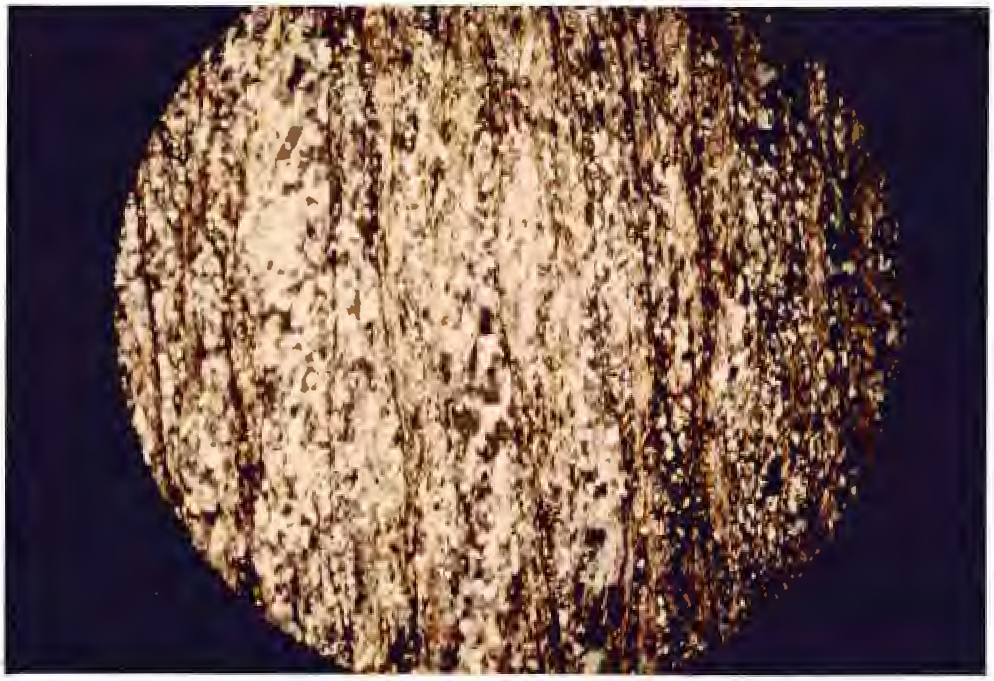


Figure 31. Photomicrograph of a blastomylonite. Note the absence of phenocrysts and porphyroclasts, the spaced schistosity, and the fluxion structure. Crossed polars. Sample ATH: 51-2. Field of view is 7 mm across.

At Athens County Park, phenocrysts or porphyroclasts are not present and the protolith is very difficult to determine (Fig. 31). This unit occurs about 250 feet southwest of a meta-rhyodacite unit. The rock is classified as a blastomylonite as it exhibits streaking and fluxion structure, and neomineralization-recrystallization appears dominant over cataclasis. It may originally have been a vitric tuff, a sediment, or a highly sheared felsic igneous rock.

It is possible that strain resulting from shearing stresses is more easily assimilated in volcanic rocks, as compared to coarser-grained intrusive rocks, and that this assimilation occurs principally in the groundmass. With recrystallization often occurring simultaneously with deformation, little to no evidence of the stress environment may be apparent, especially when phenocrysts or porphyroclasts are lacking in the rock.

Meta-plutonic Rocks

Introduction

The metamorphic terrane in northwestern Marathon County has been intruded in a number of places by plutons of tonalitic to granitic composition along with several gabbroic bodies. The felsic intrusives all show cataclastic textures and are classified according to Higgins (1971).

Felsic Plutonic Rocks

Tonalitic and granodioritic mylonite gneisses are present as intrusives into metavolcanic rocks in Marathon County Park in Athens, Wisconsin, along Black Creek 2 miles east of Athens, and near Drewek Creek 3 miles southeast of Athens. Mineralogically, biotite, hornblende, or both are conspicuous in the quartzofeldspathic rocks and often impart a weak to moderately strong foliation to the rocks.

Granitic mylonite gneisses intrude gneissic rocks along Black Creek 3 miles northwest of Athens, and along Rib River 6 miles northeast of Athens. Mineralogically, the rocks consist of microcline, quartz, and plagioclase, with biotite as the common mafic mineral.

Sixteen samples of cataclastic felsic intrusives were selected for sectioning and microscopic study. Modal analyses of 8 samples are given in Table 3. The sample locations are listed in Appendix I.

Twelve thin sections of tonalitic and granodioritic mylonite gneisses were examined. The samples are holocrystalline, inequigranular, and display cataclastic textures. The tonalitic rocks contain plagioclase (An_{10}), 20-35 percent quartz, muscovite and occasional biotite, and little to no potassium feldspar. Accessory minerals include chlorite, calcite, epidote, sericite, and minor sphene, zircon and apatite. The same mineral assemblage is present in the granodioritic rocks, although K-feldspar is present in greater amounts. Texturally, the rocks are classified as mylonite gneisses, having fluxion structure, recrystallization-neomineralization dominant over cataclasis, and greater than 30 percent of the rock being composed of porphyroclasts.

Plagioclase occurs as medium- to coarse-grained, subrounded to rounded porphyroclasts and as fine-grained "matrix" minerals. The unrecrystallized plagioclase porphyroclasts often show bent twin lamellae, fractures

Table 3. Modal Analyses of Felsic Plutonic Rocks

MINERALS	SAMPLES							
	55-7	60-1	60-2	61-1	51-14	59-1	59-5	58-20
Plagioclase	11.0	1.7	16.8	14.9	32.2	41.2	42.7	47.6
K Feldspar	47.5	74.3	42.6	53.5	8.5	3.9	2.9	-
Quartz	36.7	10.2	38.0	25.2	25.2	39.5	20.0	34.6
Muscovite	1.7	-	0.6	0.9	6.0	3.3	0.4	6.5
Biotite	2.2	-	-	3.6	21.0	-	-	-
Sericite	0.3	-	0.9	0.8	4.4	4.8	2.6	6.1
Chlorite	-	-	-	0.2	-	5.6	13.2	3.3
Epidote	-	1.3	0.5	0.3	-	-	13.6	-
Carbonate	-	-	-	-	1.8	0.9	2.6	1.9
Opaques	-	-	-	-	-	0.2	1.2	-
Sphene	-	-	-	-	0.6	0.3	0.6	-
Zoisite	-	12.4	-	-	-	-	-	-
Garnet	-	-	0.2	-	-	-	-	-
Apatite	-	-	0.2	0.2	0.3	-	0.1	-
Allanite	-	-	-	0.3	-	0.3	-	-
Saussurite	0.5	-	-	-	-	-	-	-
TOTAL	99.9	99.9	99.8	99.9	99.9	100.0	99.9	100.0

Samples 55-7, 60-1, 60-2, and 61-1 would be classified as granites (see Appendix II). Samples 51-14, 59-1 and 59-5 are granodiorites. Sample 58-20 is a tonalite.

and comminution, and rotation of the grains into the plane of foliation (Figs. 32 and 33). Saussuritization and sericitization of plagioclase is common. Finer-grained plagioclase occurs with quartz and other minerals in a crystalloblastic "groundmass mosaic" and with quartz in recrystallized veinlets. Plagioclase compositions, as determined by the Michel Levy method, range from An_4 to An_{15}.

Quartz is fine- to medium-grained, comminuted, and oftentimes elongated or rounded. Irregular boundaries and undulose grains are common, with sharper extinction and polygonal boundaries developed where recrystallization has occurred. Mortar textures are often present.

Muscovite occurs as both a primary and a secondary mineral. In several samples deformation has kinked and fractured the primary muscovite grains, with resultant alteration to chlorite occurring along the fractures (Fig. 34). Primary muscovite is anhedral to subhedral and ranges up to 4 mm in length. Elsewhere, muscovite occurs as fine-grained, subhedral laths within the matrix.

Potassium feldspar, when present, occurs as both porphyroclasts and finer-grained matrix material. Like plagioclase, the K-feldspar porphyroclasts are often fractured and comminuted, and altered to sericite and carbonate. Finer-grained K-feldspar occurs with quartz, plagioclase, and other minerals in the groundmass.

Figure 32. Photomicrograph of a cataclastic granodiorite, now a mylonite gneiss. Note the mortar texture, fractured feldspar grain, and the fluxion structure. Crossed polars. Sample ATH: 59-1. Field of view is 7 mm across.

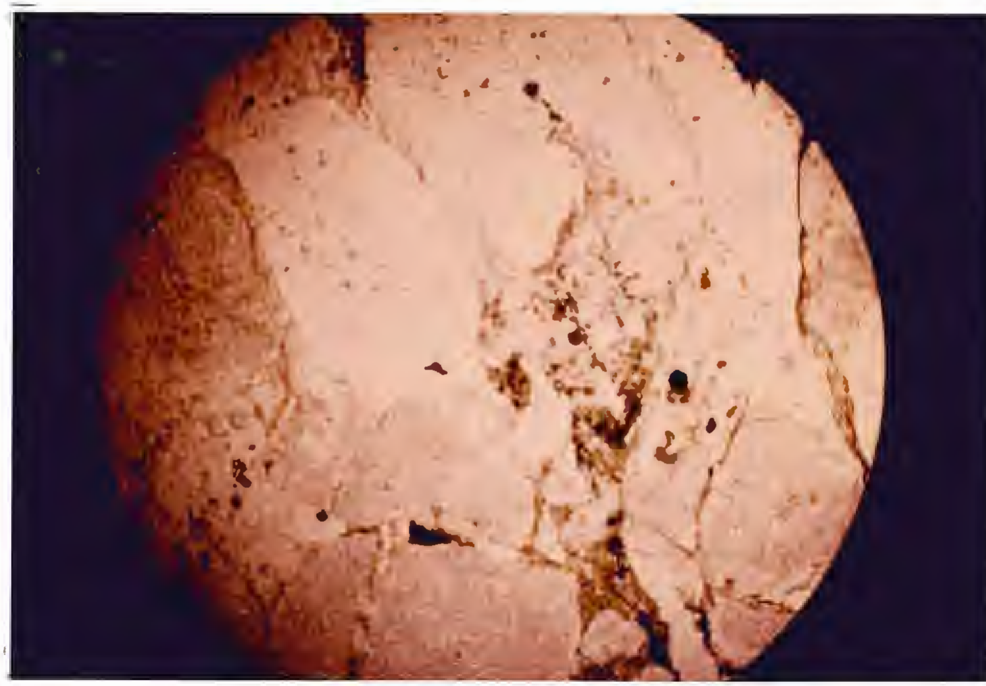


Figure 33. Photomicrograph of a cataclastic granodiorite, now a mylonite gneiss. Same view as above. Ordinary light.

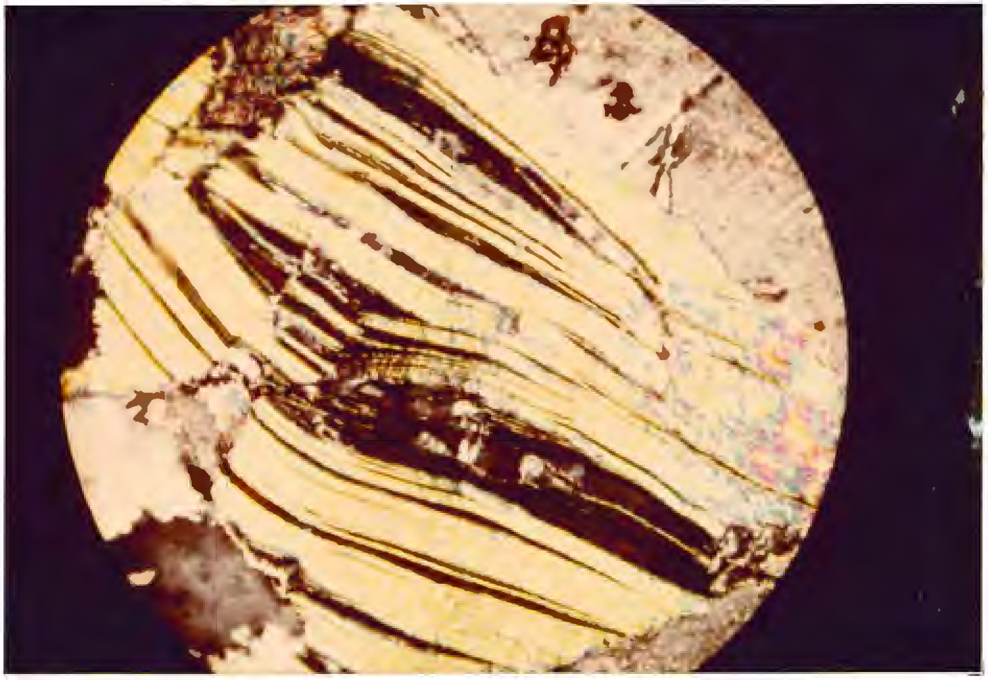


Figure 34. Photomicrograph of a kinked and fractured primary muscovite grain in a granodioritic mylonite gneiss. The dark mineral filling in the fractures is chlorite. Crossed polars. Sample ATH: 58-20. Field of view is 2 mm across.

Minor amounts of calcite, sericite, epidote, and saussurite occur as secondary replacements of feldspar and biotite. The darker minerals, such as biotite, chlorite, and opaques, also occur in minor amounts and often partially to completely surround the porphyroclasts, helping to define the fluxion structure in the rocks. In one sample, ATH: 59-5, epidote and chlorite each compose up to 13 percent of the rock.

Four thin sections of granitic mylonite gneisses were examined. Mineralogically, the granitic rocks are composed of microcline, quartz, and plagioclase with lesser biotite, muscovite, and epidote. Plagioclase compositions range from An_5 to An_{25}, as determined by the Michel-Levy method. The granitic samples are holocrystalline, inequigranular, and display cataclastic textures. Myrmekitic textures are common in the rocks, with wormlike bodies of quartz enclosed in sodic plagioclase replacing potassium feldspars. Porphyroclasts of microcline and plagioclase are often coarse-grained to pegmatitic, and a crude fluxion structure is visible only in hand specimen. Fractured, anhedral almandine garnet is present in one of the granitic samples, with fine-grained biotite laths filling the fractures (Figs. 35 and 36). In sample ATH: 60-1, 13 percent of the rock consists of fibrous zoisite and approximately 2 percent of anhedral epidote, which occur as irregular intergrowths between comminuted quartz and feldspar porphyroclasts.

Mafic Intrusive Rocks

In northwestern Marathon County several small mafic bodies crop out as ridges within the metavolcanic terrane. The units appear to parallel the boundary between the gneiss terrane and the metavolcanic terrane which trends approximately N75°E through Athens, Wisconsin. The mafic units consist of massive, metamorphosed diabase dikes and/or sills, an anorthosite unit, and weak to moderately foliated hornblende-

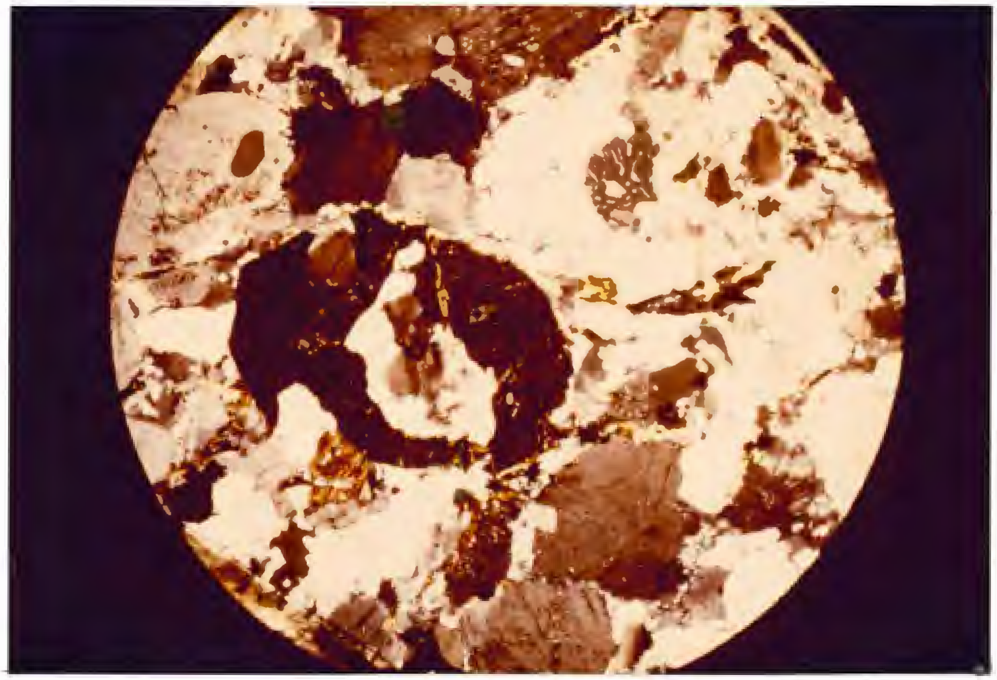


Figure 35. Photomicrograph of a granitic mylonite gneiss containing garnets and myrmekitic textures. Crossed polars. Sample ATH: 60-2. Field of view is 7 mm across.

Figure 36. Photomicrograph of a granitic mylonite gneiss. Note the biotite laths filling in the fractures in the garnet. Same view as above. Ordinary light.

actinolite schists. Megascopically, outcrop exposures are dark green to black on the weathered surface and fresh fracture. The units are locally cut by 2- to 3-inch wide quartz dikes, which have been locally faulted (Fig. 37).

Fifteen mafic rock samples were studied in thin section. The samples are fine- to coarse-grained rocks of gabbroic and dioritic composition. Six of the samples are massive and were termed diabase accordingly. Nine of the samples exhibit a weak to moderate foliation and thus were termed schists. All of the mafic rocks have been metamorphosed and show varying degrees of alteration and recrystallization to greenschist facies.

The mafic rocks are typically holocrystalline, inequigranular, and fine- to coarse-grained. Mineralogically, the rocks are composed largely of hornblende and/or actinolite, plagioclase, epidote, and sphene, with minor amounts of quartz, potassium feldspar, chlorite, calcite, sericite, saussurite, magnetite and pyrite, apatite and possible zircon, also present.

Amphiboles make up from 30 to 80 percent of the rocks. Highly pleochroic green to brown crystals were identified as hornblende and pale green crystals as actinolite. Actinolite generally occurs as fine- to medium-grained fibrous crystals in parallel, subparallel or radial aggregates (Fig. 38). Actinolite less

Figure 37. Photograph of a massive metadiabase unit cut by a quartz vein; both have been faulted. The ruler is six inches long. Sample ATH: 57-1.

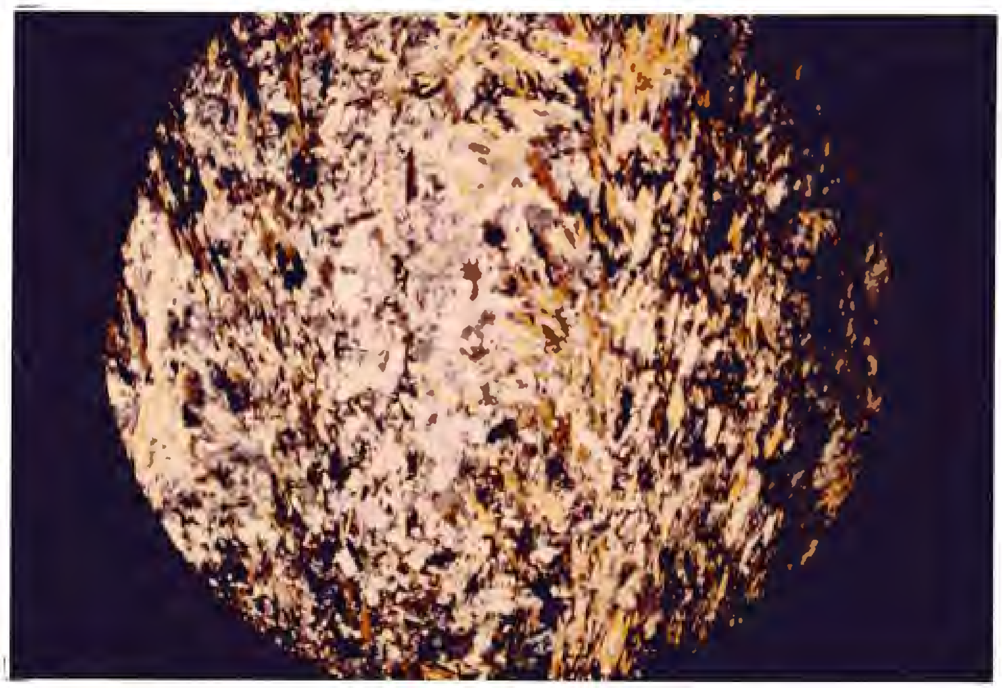


Figure 38. Photomicrograph of a moderately foliated hornblende-actinolite schist. Note the parallel aggregates of fibrous actinolite. Crossed polars. Sample ATH: 52-17. Field of view is 7 mm across.

commonly occurs as fine-grained needles in plagioclase. Hornblende generally occurs as fine- to coarse-grained, anhedral plates and fibrous laths. Hornblende and actinolite often have very irregular, ragged boundaries, and are often poikilitic with inclusions of plagioclase, epidote, sphene, and quartz. The occurrence of fibrous amphiboles is probably the result of the alteration of pyroxenes due to low-grade greenschist facies metamorphism.

Plagioclase ranges from 20 to 50 percent of the rock in the diabases and schists, and up to 85 percent of the rock in the anorthosite unit. It occurs as fine- to medium-grained, anhedral to subhedral plates and laths. The grain boundaries are often ragged and irregular, and fractured or bent laths are not uncommon (Fig. 39). Few plagioclase determinations using the Michel-Levy method could be made due to lack of twinning and alteration. However, several of the samples (ATH: 49-1 and ATH: 52-25) have compositions of andesine and labradorite. In some samples the feldspar crystals are clear and fresh, in others they are heavily charged with minute inclusions of epidote, amphibole, and opaques. In still others they are thoroughly altered to cloudy masses of saussurite, accompanied by albite, quartz, calcite, and chlorite. Such saussuritic alteration probably resulted from low-grade greenschist facies metamorphism.

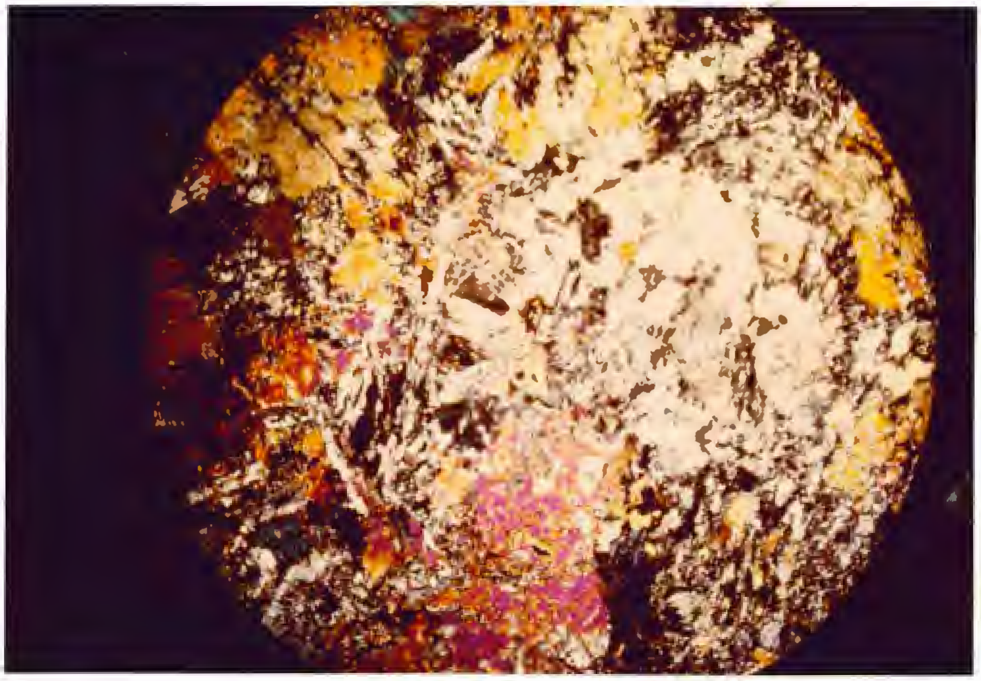


Figure 39. Photomicrograph of a massive meta-diabase. Note the large poikilitic hornblende crystals and the ragged, altered plagioclase. Crossed polars. Sample ATH: 52-19. Field of view is 7 mm across.

Epidote and chlorite are generally closely associated with actinolite and hornblende and range from a few percent to 15 percent of the mafic rocks. They occur both as alteration products in plagioclase, actinolite, and hornblende grains, and as interstitial anhedral grains. Epidote occurs as fine-grained, anhedral to subhedral crystals, whereas chlorite is most often observed as fibrous aggregates and amorphous replacement material. Epidote is the only mafic mineral present in the anorthosite unit (ATH: 59-3) and occurs as fine-grained, anhedral crystals between plagioclase laths.

Sphene is present in trace amounts and up to 10 percent of the rocks. It is closely associated with amphibole and occurs as fine-grained, anhedral to subhedral granules.

Quartz generally comprises 4-5 percent of the rocks and may be absent in some samples, as in the anorthosite unit. It occurs as anhedral, undulose grains up to 1 mm in diameter. Discrete quartz grains are interstitial with K-feldspar crystals between plagioclase and amphibole, and commonly occur as inclusions within these minerals.

Other minor constituents such as potassium feldspar, calcite, saussurite, sericite, apatite, and opaques generally make up from trace amounts to 5 percent of the total rock composition. Potassium feldspar occurs in minor amounts in six of the samples as fine-grained, anhedral, interstitial grains. Opaque oxides are most abundant, commonly occurring as anhedral crystals or secondary minute granules. Magnetite may be altered to fine-grained leucoxene and iron oxides. Apatite and zircon occur as subhedral to anhedral crystals, less than 0.1 mm long, in trace amounts interstitially or within feldspar laths. Other secondary minerals including sericite and calcite, range from trace amounts to several percent of the rock. Sericite occurs as aphanitic to fine-grained crystals, while calcite occurs as anhedral patches commonly replacing feldspar. Saussurite is also present in trace amounts, occurring as cloudy anhedral masses in altered plagioclase grains.

Interpretation of Petrology

Gneissic Rocks

Foliated rocks of high metamorphic grade are generally products of regional metamorphism involving deformation at high temperatures and pressures. In northwestern Marathon County the gneisses are typically composed of a quartzofeldspathic assemblage containing quartz-microcline-plagioclase-biotite-muscovite or a mafic assemblage consisting of hornblende-plagioclase-epidote-almandine-biotite(-quartz). The mineral assemblages are diagnostic of amphibolite facies metamorphism under moderate to high temperature and pressure conditions. Quartzofeldspathic assemblages may be derived from rocks of rather diverse kinds, including felsic igneous rocks, sandstones, and graywackes. The presence of myrmekitic textures in the granitic and quartz monzonitic gneisses may suggest a felsic plutonic protolith for these rocks. Mafic assemblages may also be derived from a variety of rock types, including mafic igneous rocks and marls.

Compositional- and color-banding are locally present in the gneisses, and the rocks are everywhere foliated. Microscopically, there is an obvious preferred orientation of hornblende and/or biotite grains, which defines a gneissosity, a lineation, or both.

Textural relationships in the gneisses indicate textural disequilibrium conditions during recrystallization. Two lines of evidence support this conclusion. The first is the presence of undulose and strained quartz grains with the development of subgrains and irregular, sutured grain boundaries. Locally, conditions approached textural equilibrium as indicated by the presence of strain-free grains and straight grain boundaries. The second line of evidence for textural disequilibrium are the bimodal grain sizes. Quartz grains in the gneisses are 0.1 and 1 mm in diameter; plagioclase is 0.5 and 2 mm in length; and biotite is 0.1 and 2 mm in length. The smaller grain sizes typically occur in the groundmass whereas the larger grains are present in pods or lenses. It is noted that this bimodality may indicate a relict igneous texture or grain size rather than a disequilibrium recrystallization texture.

The presence of migmatites in the gneissic terrane is further evidence for regional metamorphism involving deformation at high temperatures and pressures. As in most areas, the migmatites cannot be traced back to stratigraphically equivalent but unaltered rocks. Further, critical textural and compositional evidence for the primary process of migmatization appears to have been obscured by recrystallization.

At Goodrich Dells the rocks show local progressive shearing of a granitic gneiss. The gneiss is mineralogically distinct from the granodioritic and amphibolitic gneisses at this location. Granitic protomylonites have been developed from a granitic gneiss by shearing, and both appear to have been derived from a biotite-rich granite protolith.

The occurrence of quartzofeldspathic and amphibolitic gneisses, together with local migmatites and cataclastic gneisses, defines a high-grade metamorphic complex in northwestern Marathon County. The complex represents a high-grade infrastructure similar to mantled gneiss domes which have been described (Eskola, 1949) as dome-shaped cores of old crystalline rocks that are interpreted as having been metamorphosed, remobilized, or partly melted and as having intruded their overlying (stratified) mantle rocks.

The complex is lithologically distinct from greenschist facies metavolcanic rocks which lie to the south. The contact between these two terranes contains an assortment of cataclastic rocks derived from both terranes. The cataclastic gneisses present in the town of Athens (SW$\frac{1}{4}$, Sec. 31, T30N, R4E), and in Athens County Park (SW$\frac{1}{4}$, Sec. 6, T29N, R4E) are closely associated with deformed volcanic rocks in the area. The occurrence and association of these rocks may define a tectonically controlled braided shear zone separating amphibolite facies rocks to the north from greenschist facies rocks to the south.

Other high-grade infrastructures have been described in the literature which are separated tectonically from a lower-grade suprastructure by a relatively thin zone having a steep metamorphic gradient with or without complex shearing (Wegmann, 1935; Haller, 1956b, 1958, 1962; Misch and Hazzard, 1962; den Tex and Vogel, 1962; Zwart, 1963; Reesor, 1965; Armstrong and Hansen, 1966; Hyndman, 1968a; Fontielles and Guitard, 1968; Campbell, 1970; and Fyson, 1971).

Meta-volcanic Rocks

Volcanic rocks ranging in composition from basalt to rhyolite are exposed in the study area southeast of a line trending approximately N75°E through Athens, Wisconsin. The rocks have been locally metamorphosed and deformed to greenschist facies. The volcanic sequence has been disrupted by faulting and intrusion although primary textures and structures are well preserved where the rocks are not highly deformed. The spatial relationships and mineralogical similarities of the felsic volcanic and plutonic rocks suggests the plutons may have been emplaced in their own volcanic debris.

Meta-plutonic Rocks

Felsic Plutonic Rocks

Tonalitic to granitic plutonic rocks exhibiting varying degrees of cataclastic textures intrude both the gneissic and metavolcanic terranes. The deformation features are not confined to the borders of the plutons, implying deformation during emplacement, but appear to be pervasive textures, suggesting deformation occurred after emplacement of the intrusions.

The granitic rocks in Marathon County (with the exception of the Wolf River Batholith and syenite bodies near Wausau) are believed to have been emplaced 1840 to 1820 m.y. ago during the Penokean Orogeny. The various plutons show similar widespread cataclastic foliation, and many have gradational contacts from quartz diorites to granites. LaBerge (1980) suggests the various granitic rocks are co-extensive at depth and may form a large composite batholith.

Mafic Plutonic Rocks

Gabbroic to dioritic dikes and/or sills intrude the metavolcanic terrane in northwestern Marathon County, and appear to parallel the boundary between the gneiss and metavolcanic terrane. The mafic rocks have been metamorphosed to greenschist facies with typical mineral assemblages consisting of chlorite-epidote-albite-(calcite), chlorite-epidote-actinolite-albite, and actinolite-epidote-albite.

STRUCTURAL GEOLOGY

Penetrative Structures

Foliation and Schistosity

Foliation planes in the gneissic terrane are defined by the preferred orientation of hornblende and biotite grains, and by quartz-feldspar aggregates. Both dimensional and lattice preferred orientations were observed microscopically in the gneissic rocks. Foliations in the banded amphibolite gneisses and migmatites at Goodrich Dells (SE$\frac{1}{4}$, Sec. 25, T31N, R3E) are defined by hornblende-rich compositional bands, which in many cases are folded on a small outcrop scale. The attitude of the foliation surface was measured where this folding had not occurred. Within the gneissic terrane the foliation planes are dipping steeply to the north (60°-80°), with an average strike of N79°E (Fig. 40).

Within the metavolcanic terrane foliation surfaces and schistosity are defined by the preferred orientation of layer silicates, quartz-feldspar aggregates, and rotated and/or flattened volcanic phenocrysts and rock fragments. Fluxion structure measurements were also recorded for the cataclastic plutonic rocks located in the area. These foliations are cataclastically

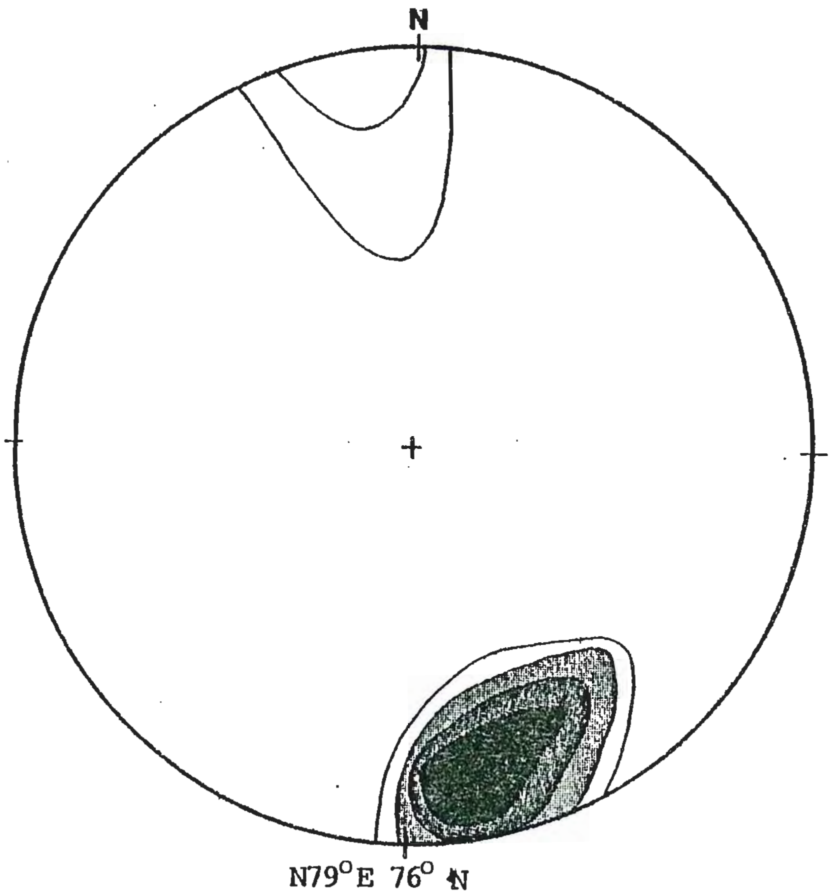


Figure 40. 79 poles to foliation planes from the gneissic terrane, plotted and contoured on an equal area projection. Contour intervals are 30, 25, 20 and 10% of data per 1% area.

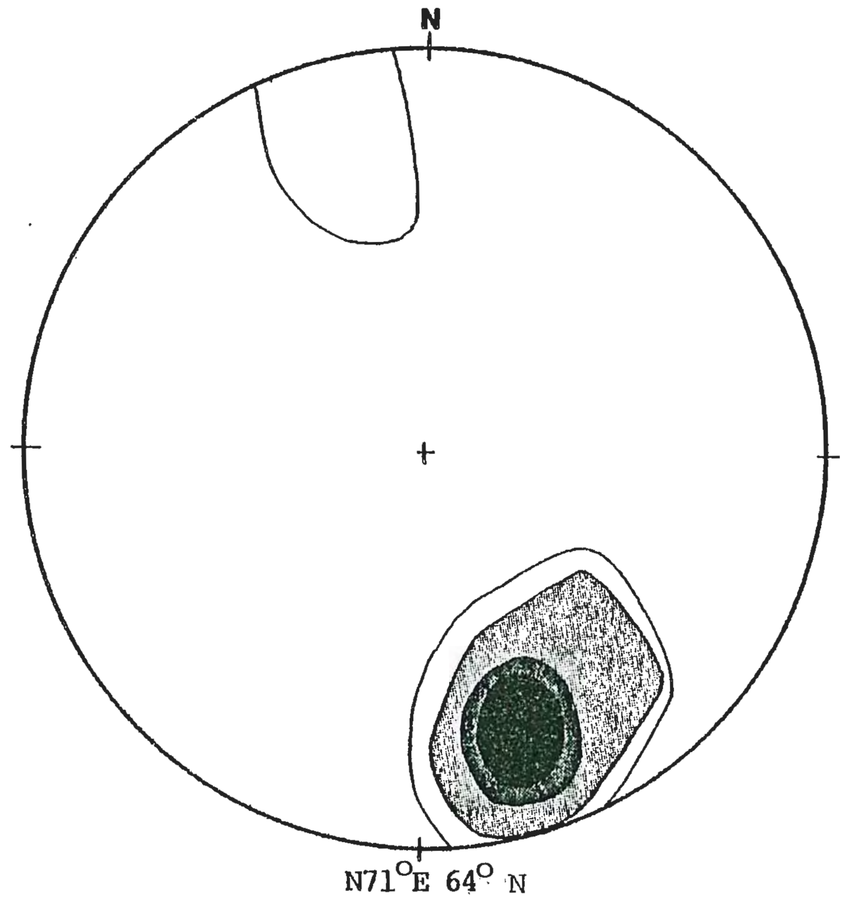


Figure 41. 269 poles to foliations and schistosity from the metavolcanic-plutonic terrane, plotted and contoured on an equal area projection. Contour intervals are 30, 25, 20 and 10% of data per 1% area.

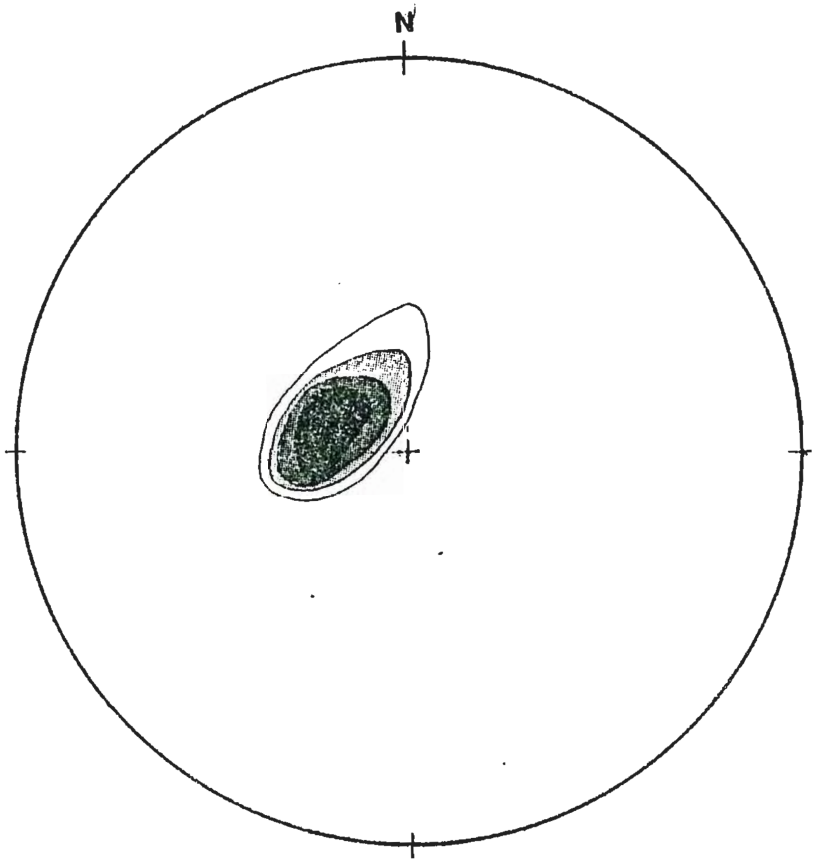
produced directed penetrative structures which commonly involve a set or family of s-surfaces. The fluxion structures are megascopically visible locally in the area. Within the schistose mafic units, weak to moderately foliated surfaces were also observed and recorded. The foliations in the metavolcanic terrane show a consistent regional orientation with dips ranging from 55° to 75° to the north and an average strike of N71°E (Fig. 41).

Foliation and schistosity data from the different terranes are approximately parallel, with foliation planes dipping steeply to the north and strikes averaging from N70°E to N80°E.

Lineations

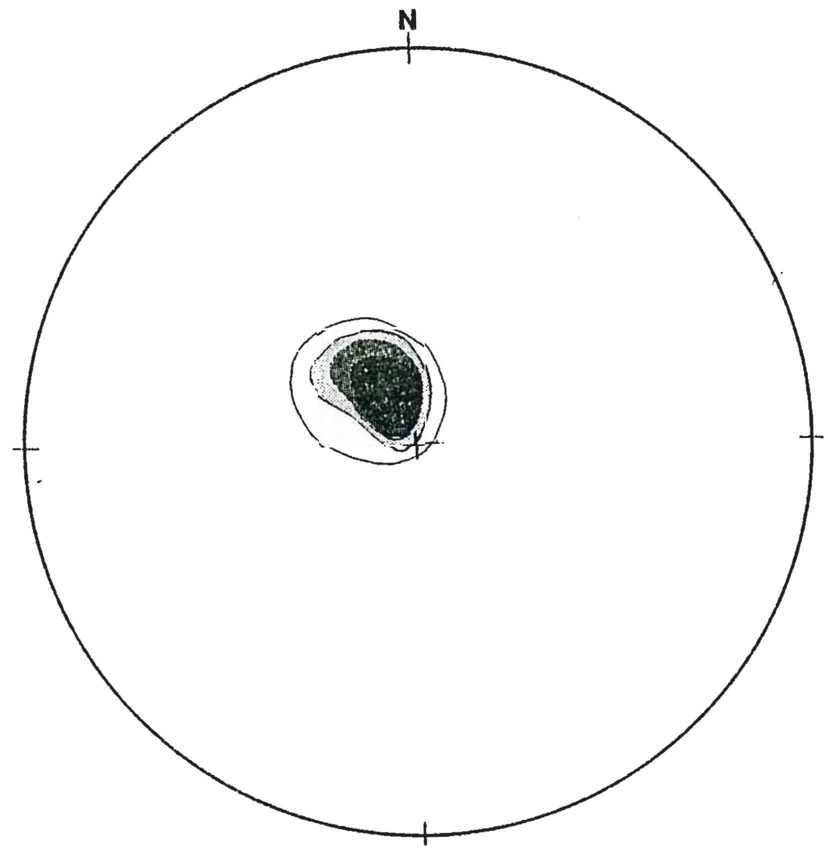
Lineations within the gneissic terrane are defined by the preferred orientation of amphibole and biotite grains, and mineral streaking. All lineations observed lie in the plane of foliation. The lineations all plunge west-northwest at 60° to 80° (Fig. 42).

The major boundary zone between the gneissic terrange and metavolcanic terrane trends approximately N75°E through Athens, Wisconsin. Along the eastern bank of Black Creek, west of Highway 97 in the town of Athens, steep to near-vertical (62°-87°) northwesterly plunging lineations were observed in gneisses and felsic metavolcanics. This is consistent with LaBerge's



N78°W 73°

Figure 42. 54 lineations from the gneissic terrane, plotted and contoured on an equal area projection at intervals of 35, 25, 15 and 5%.



N30°W 77°

Figure 43. 27 lineations from metavolcanic and cataclastic rocks, plotted and contoured on an equal area projection at intervals of 35, 25, 15 and 5%.

(1980) reported structural trends for the major boundary fault zones in Marathon County (see text below).

Lineations are also present in the metavolcanic and plutonic rocks in the study area. The lineations are defined by the preferred orientation of elongated volcanic clasts, rotated and elongated and/or boudinaged phenocrysts, single biotite grains and pods or lenses of biotites, porphyroclasts and fluxion structure, quartz-feldspar aggregates, boudinaged quartz veins, slickenside surfaces, and mineral streaking. These lineations plunge northwest at 57° to 87° (Fig. 43).

Boudinage structures are present in the metavolcanics, but with only two-dimensional exposure available their exact orientation is not known. However, at one locality in Athens County Park (NE$\frac{1}{4}$, SW$\frac{1}{4}$, Sec. 16, T29N, R4E), a three-dimensional boudinaged quartz vein cuts a mylonite unit. The boudin plunges 72° at N28°W (Fig. 44).

LaBerge (1980) reported lineations in gneissic rocks in and on the periphery of Marathon County as plunging 20°-60° west in the plane of foliation. Lineations and fold axes along the Rib River near Goodrich in Taylor County plunge 30°-40° west, fold axes in gneisses near Marshfield plunge about 20° west, lineations in amphibolites along the Little Eau Claire River in southeastern Marathon County plunge 60° south-

Figure 44. Photograph of a boudinaged quartz vein cutting a mylonite unit. Boudins are just to the left of the hammer. The boudin plunges 72° at N28°W in the plane of foliation. Athens County Park, Sec. 16, T29N, R4E.

west, fold axes in migmatitic gneisses at Greenwood in Clark County plunge 35° west, and fold axes at Neillsville in Clark County plunge 70° west (Fig. 45). LaBerge also reported that lineations in the gneisses steepen to near vertical near the major boundary fault zones in Marathon County where the gneisses are in contact with greenschist facies volcanic-plutonic rocks. Lineations measured in the gneissic terrane in the study area are fairly consistent with these reported regional structures.

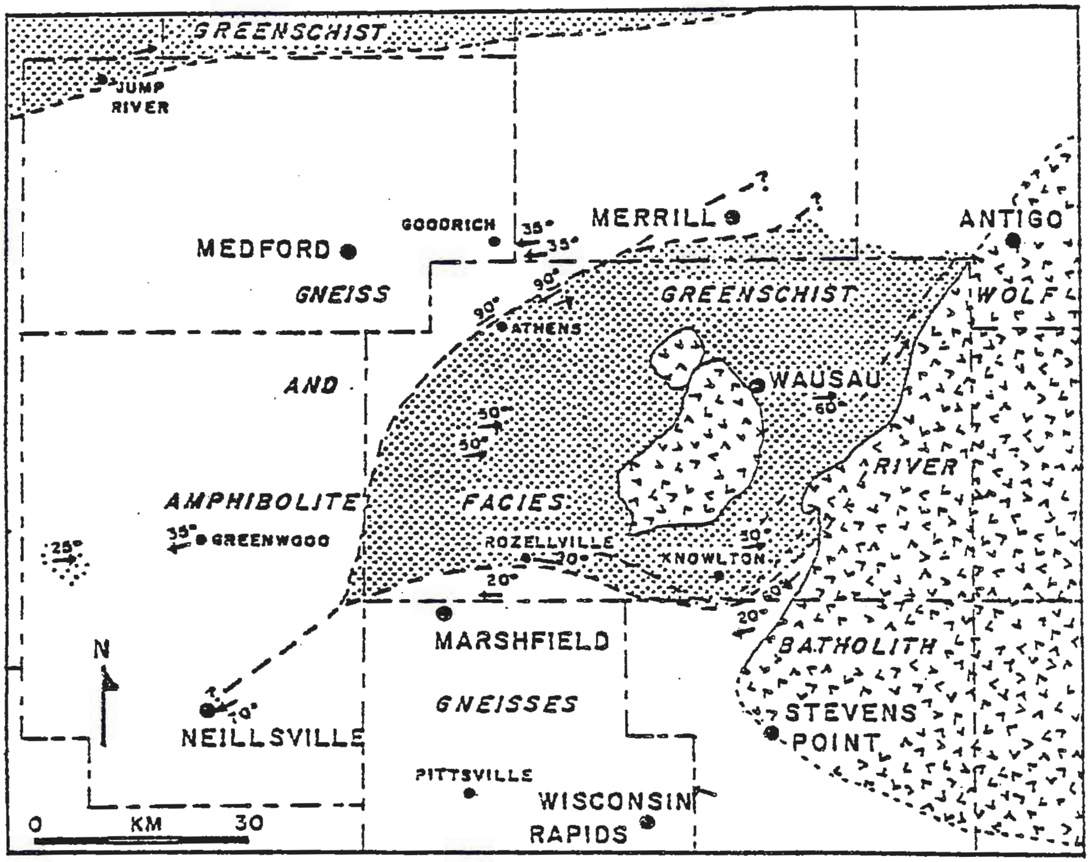


Figure 45. Simplified map of structural relationships in central Wisconsin showing the orientation of linear features in the gneissic rocks and low grade metamorphic rocks (from LaBerge, 1980).

LaBerge (1980) reported different lineation trends in deformed volcanic and plutonic rocks elsewhere in Marathon County. He reports elongated clasts and boudinaged phenocrysts plunging east at 50° or steeper in most of the volcanic pendants. Several minor fold axes also plunge steeply east to nearly vertical. Most of the measured lineations in plutonic rocks that he observed are nearly vertical with some plunging steeply to the east. He states that westerly dipping lineations are conspicuously absent in the low-grade metavolcanic rocks. In the present study area this is not the case. However, this may be due more to the proximity of this study area to a major boundary fault zone (where the rocks are more deformed) than to anything else. LaBerge (personal communication) states that along and near the major boundary fault zone the steep plunge of the lineations, rather than direction of plunge, is the important factor.

Folds

Folding is common in the amphibolite gneisses and migmatites at Goodrich Dells in Taylor County (SE$\frac{1}{4}$, Sec. 25, T31N, R3E) (Figs. 46 and 47). Types of folds include rootless intrafolial folds, open to isoclinal folds, and ptygmatic folds. Ten folds were exposed so that the trend as well as the plunge of the fold axis could be measured with some degree of confidence.

Figure 46. Photograph of folding in amphibolite gneisses and migmatites at Goodrich Dells in Taylor County (SE$\frac{1}{4}$, Sec. 25, T31N, R3E).

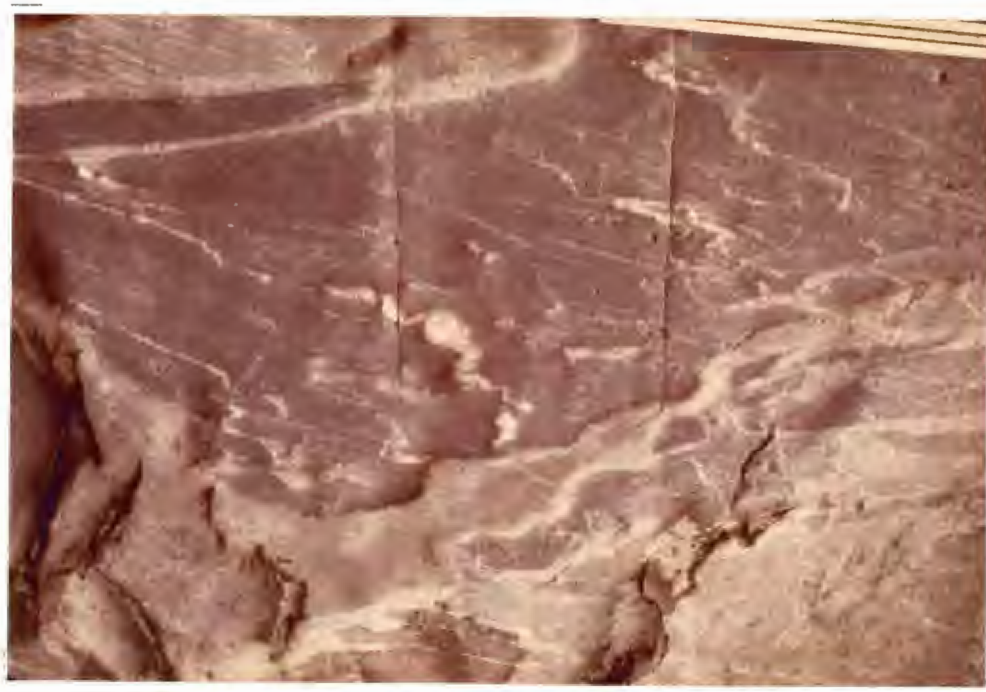


Figure 47. Photograph of a pytgmatic fold at Goodrich Dells in Taylor County.

Eight folds are steeply dipping to vertical with the strike of the trend varying between N62°E and N85°E. The plunges of the fold axes are westerly at 47° to 78°. Two of the folds have trends which strike N42°E and N50°E, with easterly plunges of 86° and 75°, respectively (Fig. 48).

Within the metavolcanic terrane minor folds were observed at two locations (Fig. 48). In the SW$\frac{1}{4}$ of Sec. 6, T29N, R5E, mafic to intermediate metavolcanics locally contain open folds with sheared-out limbs (Fig. 49). The trends of the folds strike S80°W to S86°W with fold axes plunging 72° to 88° to the west. Small scale open folds also occur locally in intermediate metavolcanics along Drewek Creek (NW$\frac{1}{4}$, Sec. 10, T29N, R4E) (Fig. 50). The trends of the fold axes here range between N87°W and N75°W. The plunges of the fold axes are west at 17° to 33°. Convergent dip isogon patterns within these minor folds indicate they are class 1b (parallel) folds (Ramsay, 1967).

Quartzose ptygmatic folds occurring with boudinage structures in a mylonite unit were observed at Athens County Park (Sec. 16, T29N, R4E) (Fig. 51). The folds have a lobate appearance and are polyclinal. The ptygmatic folds are class 1c (flattened parallel) folds (Ramsay, 1967). Ptygmatic folds are produced when there is shortening within a competent layer. Compressive stresses parallel to the layer lead to instability

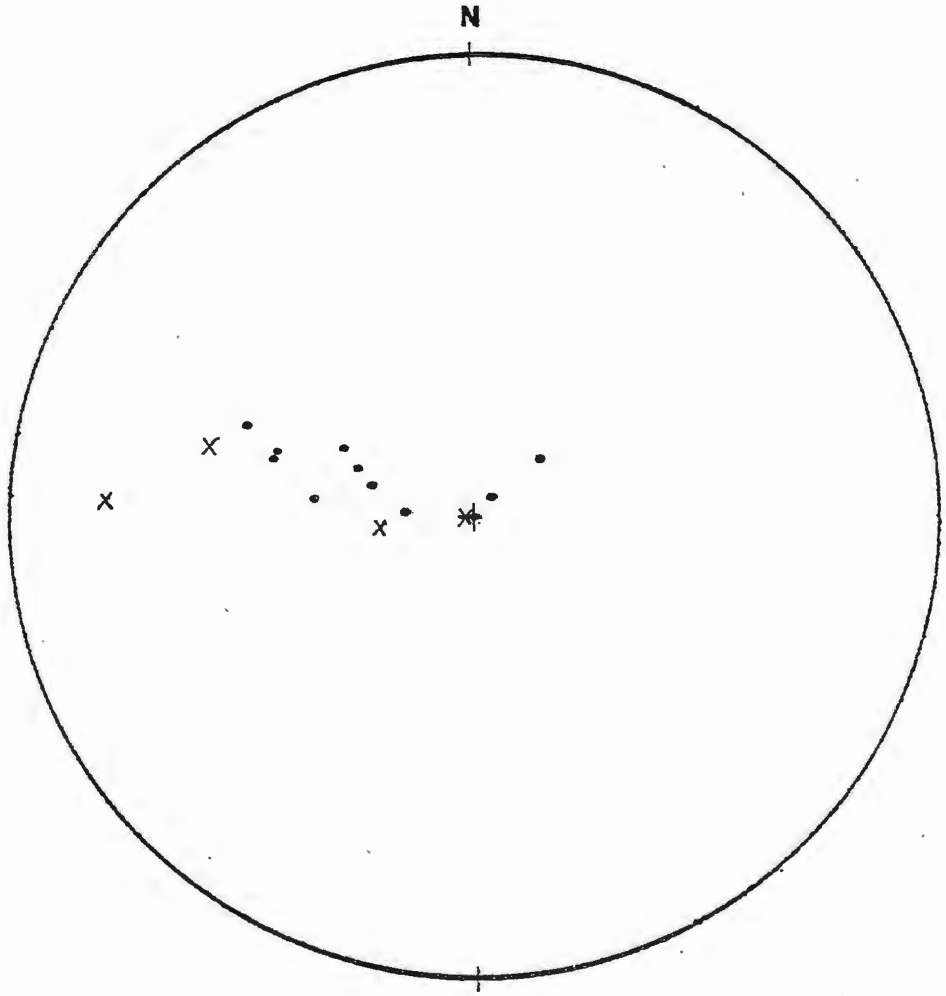


Figure 48. Plunge of 10 fold axes (dots) from amphibolite gneisses and migmatites at Goodrich Dells in Taylor County. Plunge of 4 fold axes (x's) from local folds in the metavolcanic terrane.

Figure 49. Photograph of local open folds with sheared-out limb in mafic to intermediate metavolcanics. SW$\frac{1}{4}$, Sec. 6, T29N, R5E.

Figure 50. Photograph of smallscale open folds in intermediate metavolcanics. NW$\frac{1}{4}$, Sec. 10, T29N, R4E.

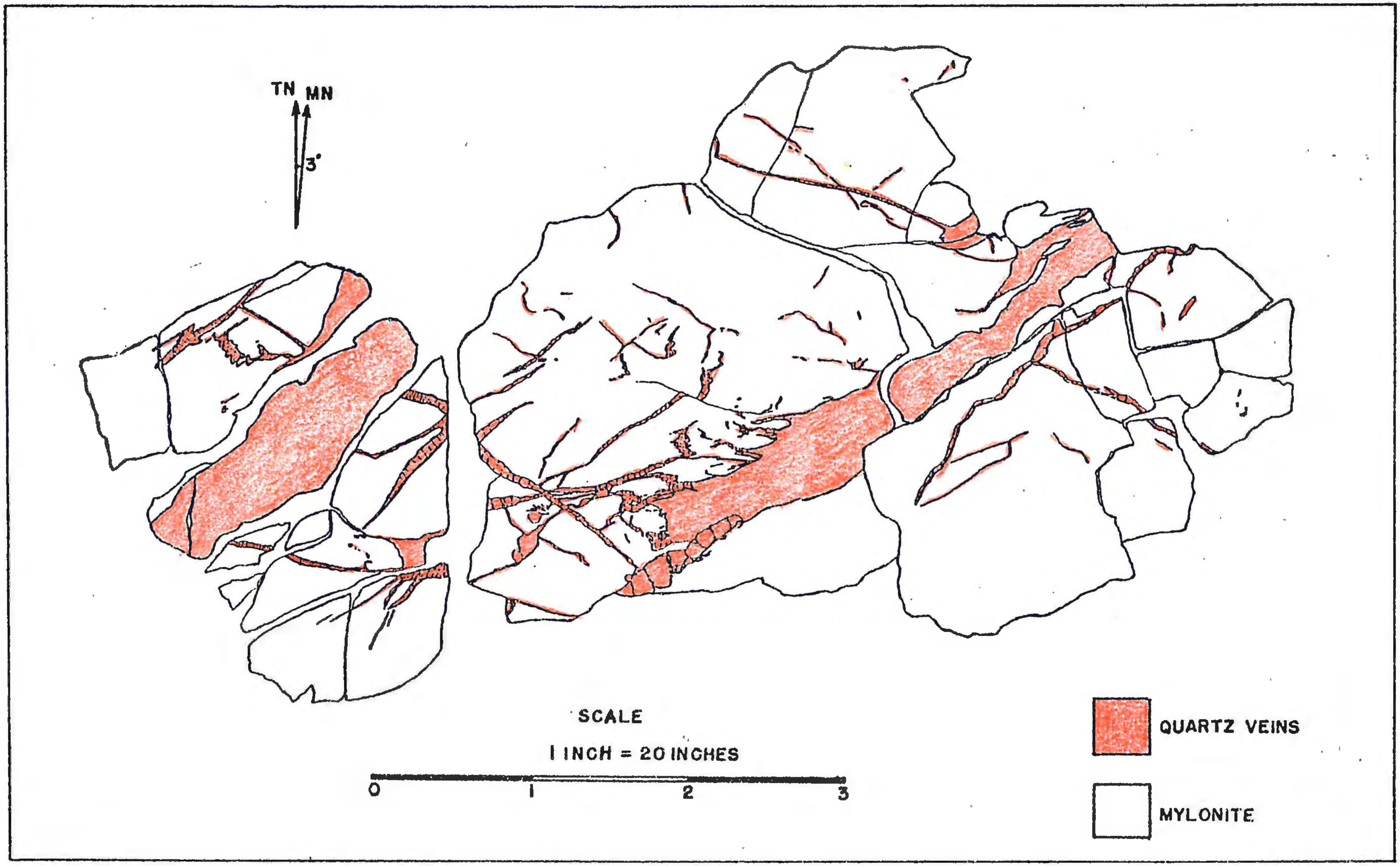


Figure 51. Quartzose ptygmatic and boudinage structures cutting a mylonite unit in Athens County Park (Sec. 16, T29N, R4E). The structures indicate maximum extension in a near vertical direction and maximum shortening in a northwest-southeast direction (i.e., perpendicular to foliation).

which causes the layer to buckle. The ptygmatic folds and boudinage structures at Athens County Park indicate extensional stress in a near vertical direction and compressive stress in a northwest-southeast direction, at right angles to the dominant foliation orientation.

Nonpenetrative Structures

Shear Zones and Faults

The Middle Precambrian volcanic-plutonic complex in Marathon County appears to be bounded on all sides by major zones of cataclastic rocks (LaBerge, 1980) (Fig. 45). One of the zones extends in a southwesterly direction along the northern edge of the volcanic-plutonic terrane in Marathon County. The fault zone has been traced from near Merrill southwest through Athens to Milan where foliation curves in a more southerly direction. LaBerge states that several ultramafic bodies occur along this northern zone of cataclastic rocks which separates gneisses, migmatites and amphibolites on the north from low-grade metavolcanic rocks to the south. The cataclastic zones in Marathon County are parallel with aeromagnetic and gravity trends.

Within the present study area, the boundary between the two major terranes is structurally concordant with geological units which trend approximately N75°E through Athens, Wisconsin. The fault zone appears to have gradational boundaries, varying in width from 1 to

4 km, and may consist of anastamosing zones of intensely deformed rocks within a broader zone of less deformed rocks. The zone crosses greenstone, amphibolite, and felsic plutonic rocks alike, resulting in a wide variety of cataclastic rocks.

In the metavolcanic terrane, several minor shear zones trend subparallel to foliation and the major boundary fault. These minor shear zones commonly contain epidote veinlets and locally are composed of slickenside surfaces (Fig. 52). At one location, in the town of Athens (SW$\frac{1}{4}$, Sec. 31, T30N, R4E), pretectonic poikiloblastic garnets in a quartzofeldspathic biotite gneiss have been rotated with resultant foliation wrapping around the garnets (Fig. 53).

Joints

69 joint measurements were recorded in the field. Poles to the joint surfaces were plotted on an equal area stereonet and contoured (Fig. 54). The greatest concentration of joint poles on the stereonet shows a preferred orientation of fracture surfaces in a northwest-southeast direction, with steep to near vertical dips. At nearly right angles to this orientation a second set of fractures trend northeast-southwest, also dipping steeply to vertical. Minor concentrations of joint poles are distributed around the center of the stereonet, representing random orientations of joints

Figure 52. Photograph of a local shear zone in intermediate metavolcanics. SE$\frac{1}{4}$, Sec. 3, T29N, R4E.

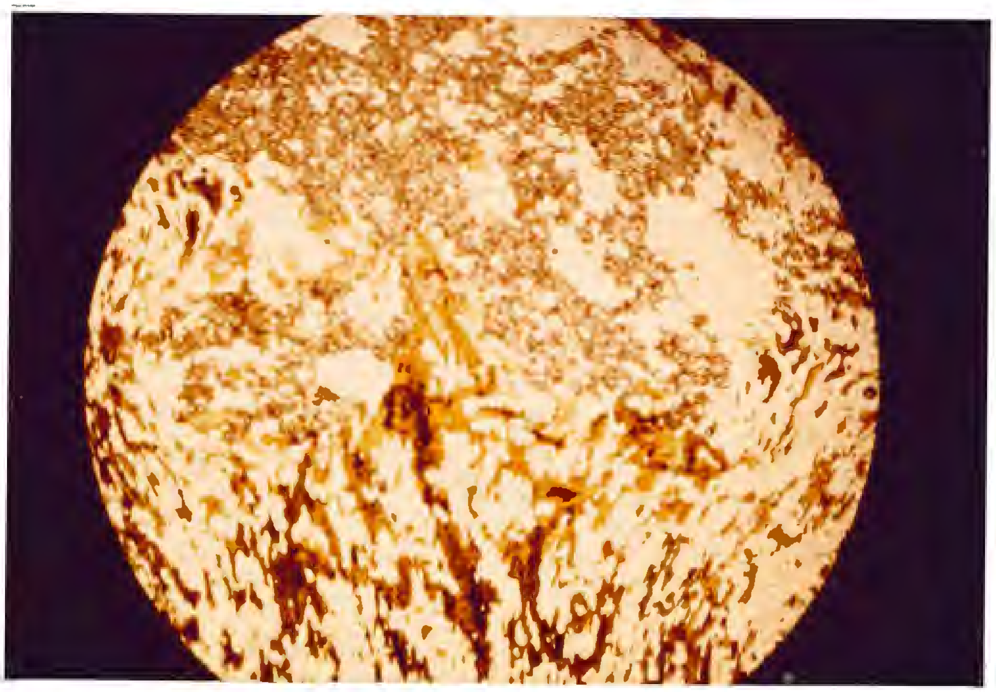


Figure 53. Photomicrograph of pretectonic poikiloblastic garnets in a quartzofeldspathic biotite gneiss. Note the foliation wrapping around the garnets. Ordinary light. Sample ATH: 52-7b. Field of view is 7 mm across.

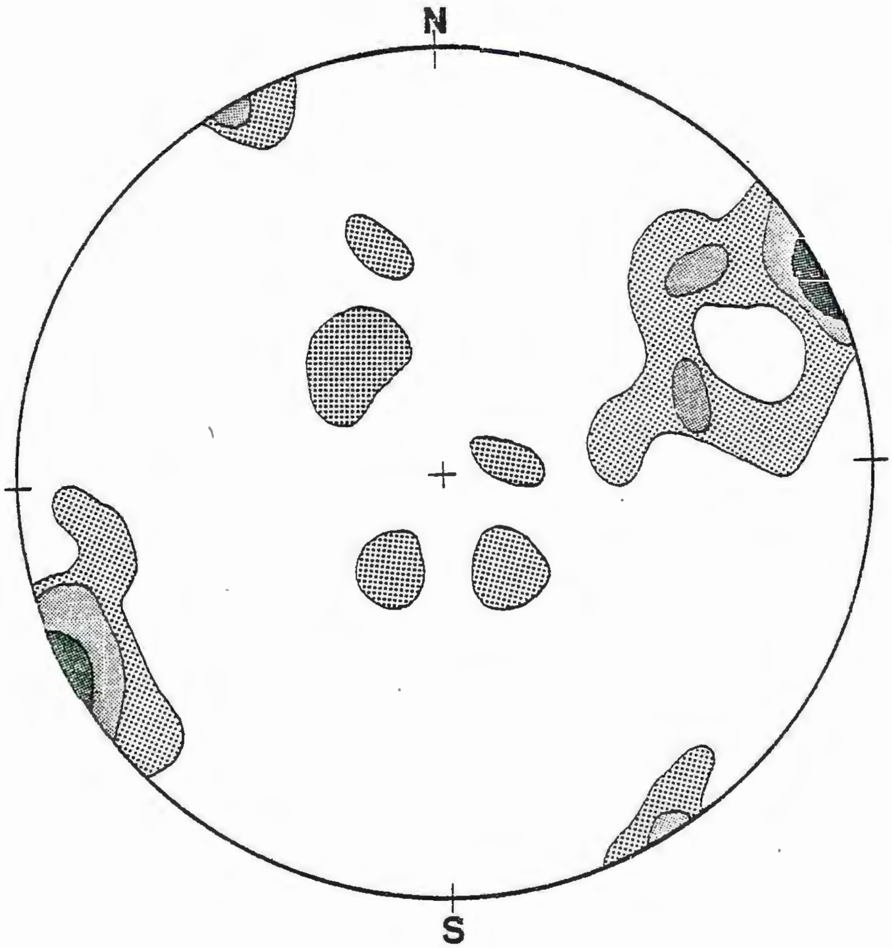


Figure 54. Contour diagram of 69 poles to joint planes in northwestern Marathon County. Poles were plotted on an equal area Schmidt net and contoured using a Kalsbeek counting net. Contours are at the 3, 6 and 9% levels of data per 1% area.

dipping at more gentle angles. The major joint system (NW-SE) is oriented perpendicular to the dominant structural trend in the area, while the second set (NE-SW) is oriented parallel to the foliation.

Quartz Veins

Quartz veins cut all major rock types in the present study area. Locally the veins are boudinaged, but commonly they are net-like structures (Fig. 55). Occasionally the veins trend parallel to foliation. The veins range from 0.5 cm to 10 cm in width.

Figure 55. Photograph of net-like quartz veins cutting a felsic metavolcanic unit. NE$\frac{1}{4}$, Sec. 10, T29N, R4E.

Strain Analysis

Analysis

Strain analysis was carried out on samples located up to 9 km from the boundary zone, as well as samples located within the zone itself (Fig. 56). This was done to analyze quantitatively total cumulative strain in the rock units (Schwerdtner and others, 1977).

When a body of rock is stressed the individual particles that make up the body are displaced to new positions. To describe these changes a strain ellipsoid is commonly used. In the three-dimensional case, three mutually perpendicular lines may always be found in the undeformed state of a body that remain mutually perpendicular in the strained state. These lines in the deformed state are parallel to the principal axes of the strain ellipsoid. In this paper, the principal axes of the strain ellipsoid are designated λ_1, λ_2, λ_3 corresponding to the maximum, intermediate, and minimum principal axes, respectively (Fig. 57).

λ_1, λ_2, λ_3 are the principal quadratic elongations and are defined by

$$\lambda = \left(\frac{l}{l_o}\right)^2 = (1 + e)^2$$

where l_o is the initial length of a line and l the length after straining. e is the elongation and is defined by

$$e = \frac{l - l_o}{l_o}$$

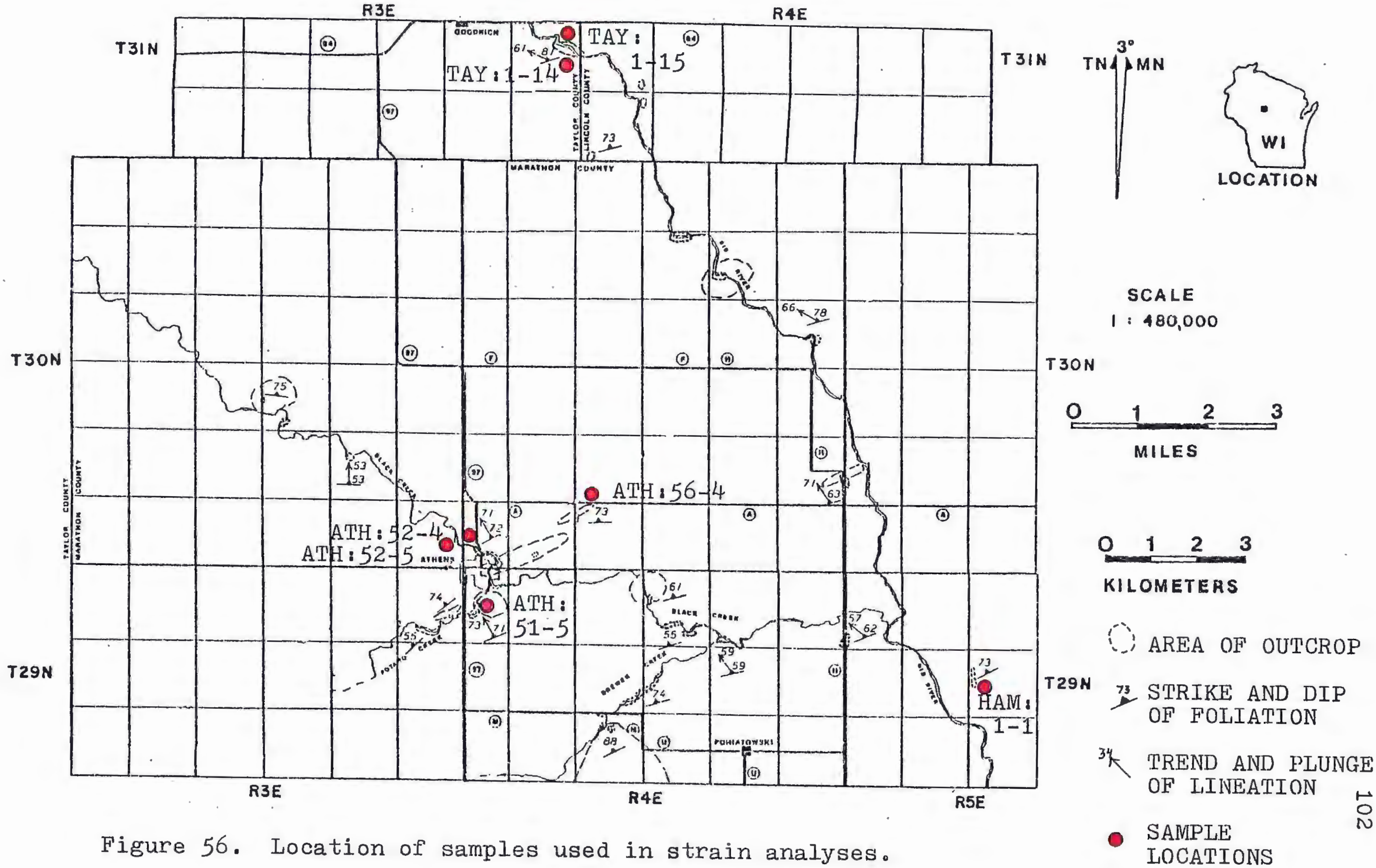


Figure 56. Location of samples used in strain analyses.

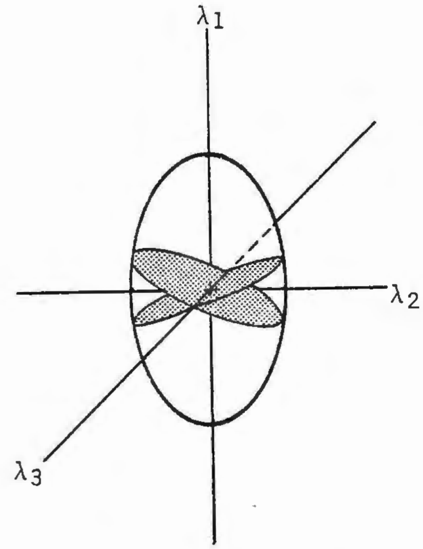


Figure 57. Strain ellipsoid illustrating the principal axes of strain in the deformed state.

Shortening is represented by a negative elongation.

For this analysis it was assumed that particles deformed homogeneously with the matrix and that no significant original pre-strain fabric was present.

Seven rock samples were collected and slabbed along 3 sets of orthogonal faces (Figs. 58 and 59). These faces were cut parallel with foliation (XY plane), perpendicular to foliation and lineation (YZ plane), and perpendicular to foliation but containing the lineation (XZ plane). At least 50 strain indicators were then measured from each face (Fig. 60). These indicators included volcanic rock fragments, volcanic phenocrysts, biotite aggregates, and quartz-feldspar aggregates. Similar results were obtained for the various indicators.

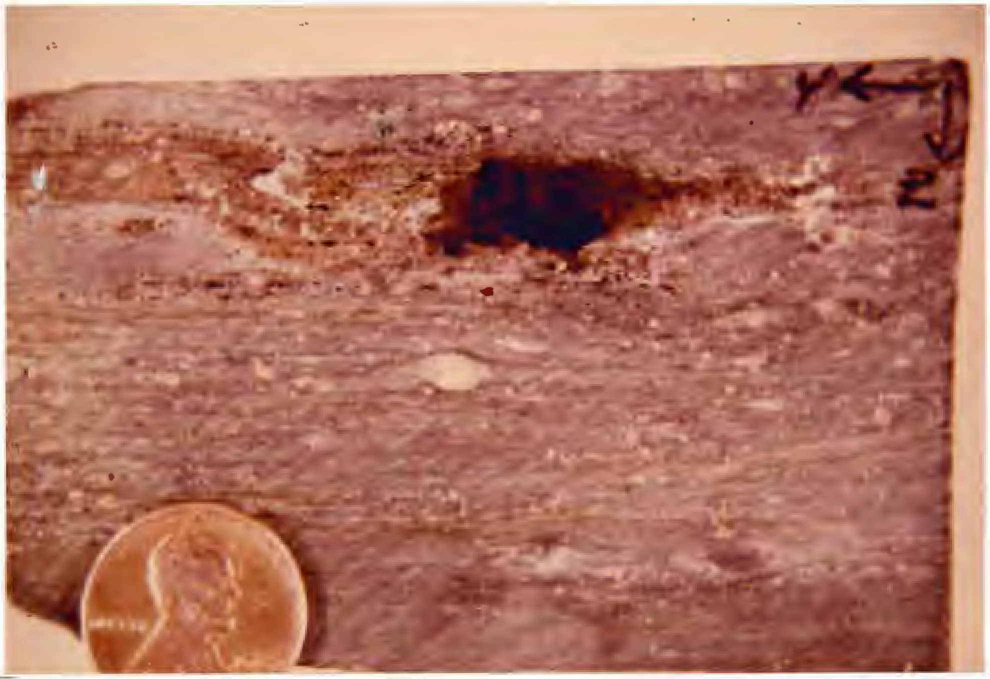
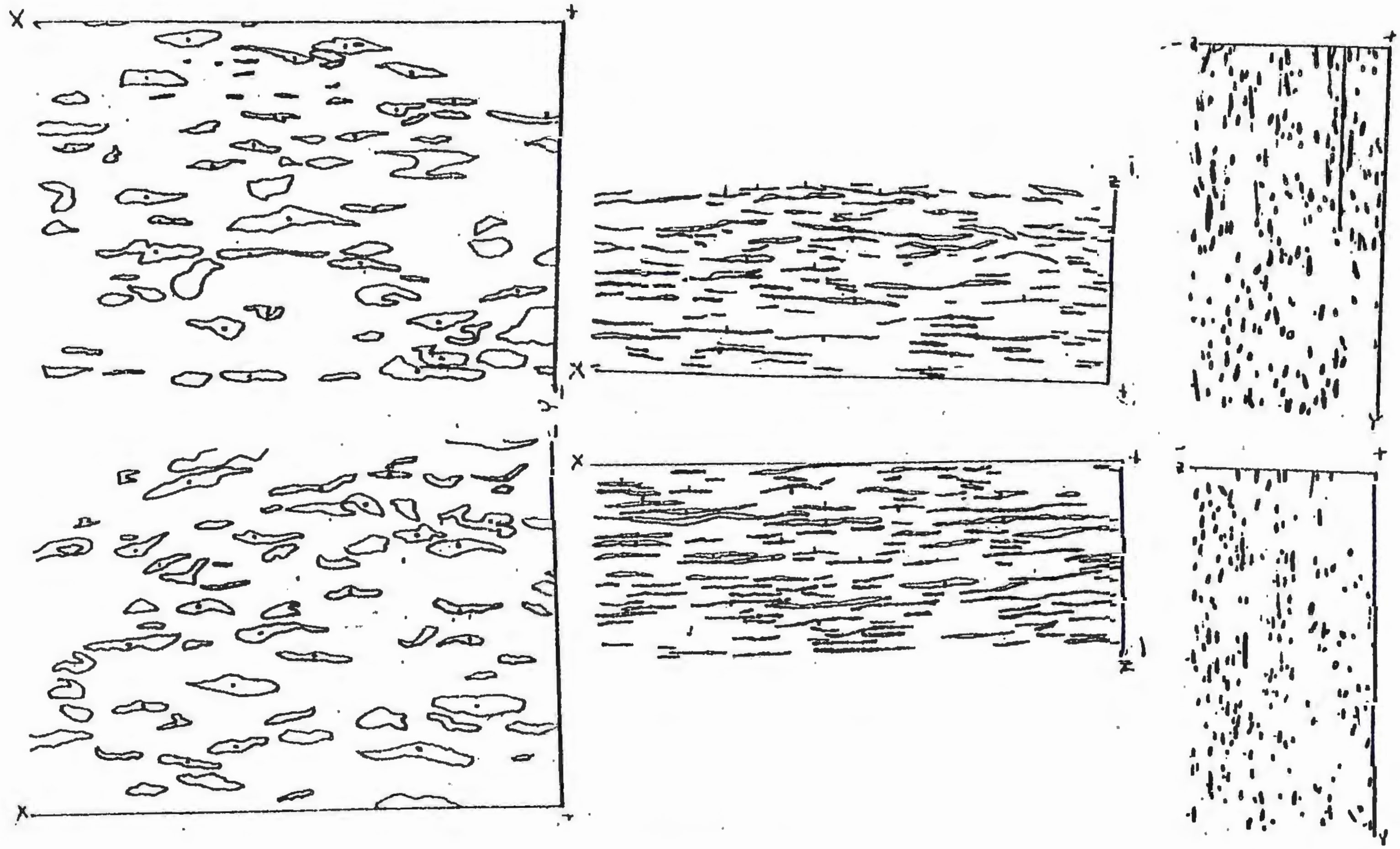


Figure 58. Photograph of a rock sample slabbed along 3 sets of orthogonal faces (foliation, lineation, and right angles to both). The YZ face is shown. Sample HAM: 1-1.

Figure 59. Photograph of a rock sample slabbed along 3 sets of orthogonal faces. The XZ face is shown. Sample ATH: 51-5.



A. XY faces B. XZ faces C. YZ faces

Figure 60. Example of rock sample ATH: 51-5 used in strain analysis. Strain indicators for this sample are biotite aggregates. Both the length of the indicators and the angle to the principal axis were measured on each of the orthogonal faces.

From the measurements on each face, the two-dimensional strain was computed using the methods of Ramsay (1967) and Elliott (1970). A best fit three-dimensional strain ellipsoid was then calculated for each sample using the Pase 5 program of Siddans (Table 4). Error limits on the dimension and orientation of the best fit strain ellipsoid and its orientation were calculated at less than 2 percent for each sample.

Results show that the maximum principal axis of extension (λ_1) in the strain ellipsoid corresponds to maximum elongation in the X direction, perpendicular to the YZ face (Fig. 61). The intermediate principal strain axis (λ_2) corresponds to intermediate elongation in the Y direction, perpendicular to the XZ face. Minimum extension (λ_3), or in this case flattening, occurs in the Z direction, perpendicular to the XY face. Thus it can be seen that the maximum elongation direction ($X = \lambda_1$) lies within the foliation plane in the study area and is parallel to lineation, whereas flattening ($Z = \lambda_3$) is oriented perpendicular to the foliation in a northwest-southeast direction. Results further indicate that the rocks were shortened up to 40 percent of their original length.

Results can be illustrated using the techniques developed by Flinn (1962). Flinn has shown that all types of homogeneous strain may be represented graphically. In Figure 62, the ratio of major and intermed-

Table 4. Measurements of the principal axes of the strain ellipsoid and Flinn values for the strain samples.

Sample No.	Principal axes of the strain ellipsoid			Flinn value k
	$X = (1 + e_1)$	$Y = (1 + e_2)$	$Z = (1 + e_3)$	
1 (TAY:1-15)	1.47	1.02	0.40	0.28
2 (TAY:1-14)	1.63	0.50	0.30	3.37
3 (ATH:52-4)	1.90	0.80	0.30	0.78
4 (ATH:52-5)	2.80	1.40	0.30	0.31
5 (ATH:56-4)	1.90	0.70	0.40	2.26
6 (ATH:51-5)	2.60	0.90	0.12	0.27
7 (HAM:1-1)	1.02	0.80	0.30	0.17

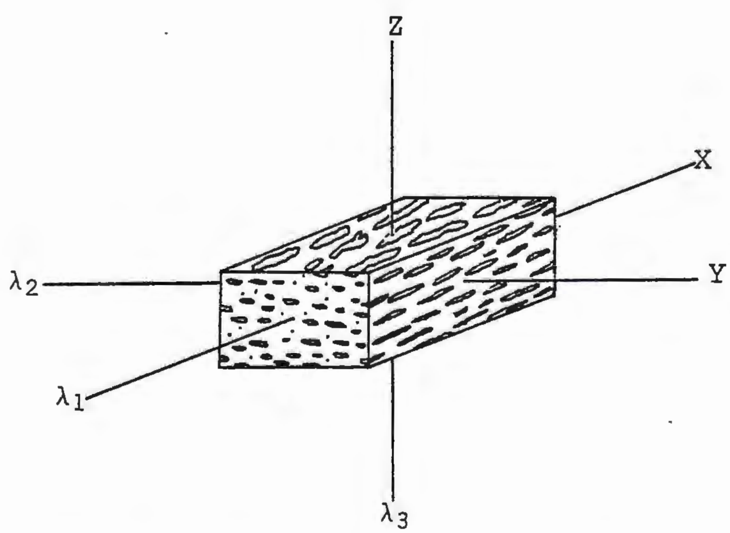


Figure 61. Strain ellipsoid for strain samples in the study area. Note maximum elongation (λ_1) occurs parallel to the X direction and maximum shortening (λ_3) occurs parallel to the Z direction.

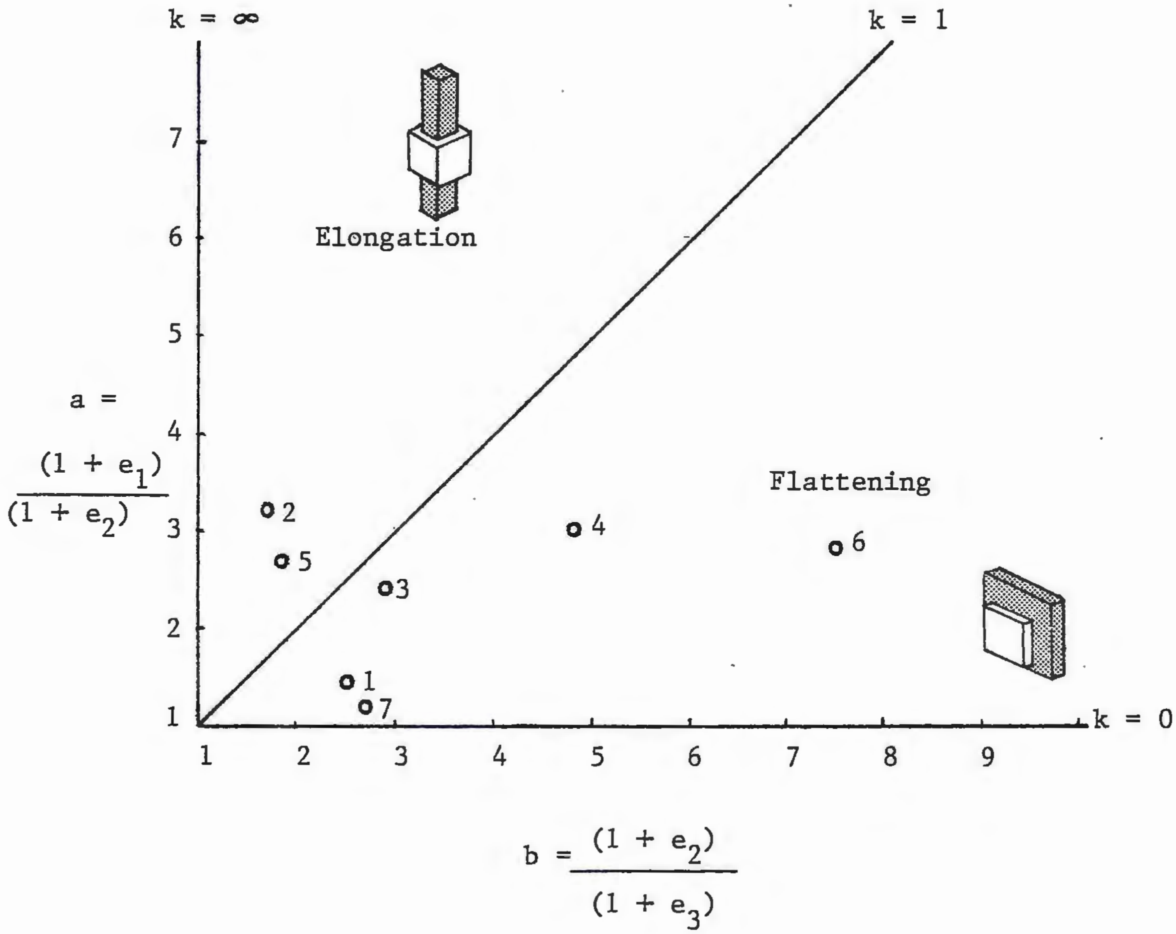


Figure 62. Flinn diagram showing plots of strain samples from the study area. The sample numbers and the principal axes of the strain ellipsoid are given in Table 4.

iate axes (a) of the strain ellipsoid is plotted against the ratio of intermediate and minor axes (b). The original of the graph is at (1, 1). If the number k is defined by

$$k = \frac{a - 1}{b - 1}$$

then Figure 62 is divided into a number of fields for different values of k. For k = 0 all strain ellipsoids are pancake in shape and indicate uniform shortening. For $0<k<1$, the deformation is of a flattening type. For k = 1, the deformation is by simple shear. For $1<k<\infty$, the deformation is of a constrictive type. For $k = \infty$ all strain ellipsoids are cigarlike in shape and indicate uniform extension.

As can be seen from Figure 62, five of the strain samples indicate deformation of a flattening type whereas samples numbered 2 and 5 indicate extensional deformation. Sample number 2 is a cataclastic gneiss located 9 km from the major boundary fault zone, and sample numbered 5 is a cataclastic metavolcanic rock located along the fault zone.

Conclusions

The following conclusions were made from the strain analysis:

1) Both the gneiss and metavolcanic terranes are characterized by a similar flattened fabric. Extensional deformation occurred locally within and along the contact between the two terranes.

2) Maximum shortening (flattening) occurred in a northwest-southeast direction and is perpendicular to foliation. The units were shortened up to 40 percent of their original length.

3) Maximum elongation lies within the foliation trend (northeast-southwest direction) and is parallel to lineation.

4) The linear fabric is not uniformly developed throughout the boundary zone.

Problems

The following problems were encountered during the strain analysis: (1) the paucity of outcrop prevents determination of the extent of cataclastic deformation in the study area, and (2) difficulties exist in distinguishing between cataclastic rocks and fine-grained, porphyritic metavolcanic rocks, both in hand specimen and thin section.

Deformation History

The main purpose of the structural analysis has been to analyze the different possible deformations that have affected the rocks in northwestern Marathon County. The structural evidence indicates two deformational phases, which represent significant readjustments in the rock accompanied by metamorphism. The two deformations are: (1) amphibolite grade metamorphism of pre-existing rocks in the gneissic terrane, greenschist facies metamorphism of volcanic rocks, and the development of a similar foliation trend in both terranes, and (2) the cataclastic deformation of gneissic and metavolcanic rocks within and near to the boundary fault zone, and the development of two major joint systems. Intrusion of mafic rocks and quartz veins, accompanied by local minor faulting, is considered to have occurred after the two main phases of deformation.

The gneissic terrane is metamorphosed to the amphibolite facies and has structures similar to those in the metavolcanic terrane. The gneisses exhibit a consistent regional orientation of both foliation and lineation, with foliation planes dipping 70° north with an average strike of N79°E, and lineations plunging 70° to the northwest in the plane of foliation. Fold axes plunge westerly at 47° to 78°.

The gneisses have not been dated radiometrically, but they may be early Middle Precambrian rocks that have been metamorphosed to amphibolite grade. The gneisses are lithologically similar to those of the "Chippewa Amphibolite Complex" which is 60 miles to the west of the study area. Cummings and Myers (1978) showed that these gneisses had undergone two periods of deformation and metamorphism prior to being intruded by 1850 m.y. old plutons. Gneisses and migmatites in Eau Claire County, which is situated just west of Marathon County and includes the Chippewa Amphibolite Complex, are believed to be Archean in age (Maass, Medaris, and Van Schmus, 1980).

Volcanic rocks in the study area were metamorphosed to greenschist facies and exhibit structures similar to those in the gneissic terrane. Foliations in the metavolcanic terrane dip 65° to the north with an average strike of N71°E, while lineations have an average plunge of 65° to the northwest in the plane of foliation. Local fold axes in the metavolcanic terrane plunge westerly at 17° to 33°.

The similarity in foliation, lineation, and fold axes attitudes suggest that the gneissic and metavolcanic terranes were deformed at the same time. Strain analysis shows foliation is perpendicular to maximum shortening and rock units in the area where flattened up to 40 percent of their original length. Maximum elongation lies within the northeast-southwest foliation trend and is parallel to lineation.

The two terranes are in contact along what appears to be a braided shear zone, and structures here are essentially similar to those elsewhere in the area. The structures produced within or near to the boundary fault seem to be the result of essentially vertical movement. For example, in the town of Athens (SW$\frac{1}{4}$, Sec. 31, T30N, R4E), gneissic rocks are juxtaposed with metavolcanic rocks in outcrop. At this locality, lines of evidence for near vertical faulting include lineation trends (plunging steeply to the northwest), and vertical slickenside surfaces.

Boudinage, ptygmatic structures, and lineations elsewhere in the metavolcanic terrane, in addition to the strain ellipsoid results from sample number 5, suggest maximum elongation was operative in a vertical to near-vertical direction, and flattening occurred in a northwest-southeast direction.

The second deformational phase is defined by the presence of cataclastic rocks derived from both terranes, slickenside surfaces, local development of a linear fabric, and two major systems of joints.

The major joint system trends northwest-southeast, perpendicular to foliation, while a second major system trends northeast-southwest, parallel with foliation. If these joint sets are tension joints, the stress field which caused their development would be consistent with the stress field which developed the foliation during the first deformational phase.

Intrusion of felsic plutons into both gneissic and volcanic rocks in the study area is likely to have occurred about 1840 m.y. ago. In north-central Wisconsin the volcanic-sedimentary sequence is intruded by Middle Precambrian granitic rocks, ranging in age from about 1840 to 1760 m.y. (Van Schmus, 1976). The older plutons are granitic to tonalitic in composition, are mainly syntectonic, and many contain a lineation which is sometimes accompanied by a weak to moderate foliation (LaBerge, 1977; Maass, Medaris, and Van Schmus, 1980). Cataclastic textures are present in all deformed rocks but are subordinate to recrystallization textures. Cataclasis occurred simultaneously with recrystallization during Penokean deformation (Maass, Medaris and Van Schmus, 1980). The younger plutons in north-central and southern Wisconsin consist of potassic granites, are post-tectonic, and generally little deformed (LaBerge and Mudrey, 1979). Thus the felsic plutons in the present study area are believed to belong to the group of older granitic plutons, based on similar compositions and the presence of pervasive cataclastic textures in the rocks.

It is possible that faulting in the area was sporadically active for an extensive period of time. The oldest recognized Early Proterozoic rocks in Wisconsin are mafic to felsic volcanics which were extruded at the beginning of the Penokean Orogeny, about 1860 m.y. ago (Maass, Medaris, and Van Schmus, 1980). Following the extrusion and deposition of volcanic flows and volcaniclastic debris, deformation began. Rocks at lower depths in the earth's crust were metamorphosed to the amphibolite facies while the volcanic rocks were metamorphosed to greenschist facies. Deformation imprinted similar structures on both these rock types. About 1840 m.y. ago, felsic plutonic rocks were intruded into the gneissic and metavolcanic rocks. Vertical faulting may have occurred prior to or simultaneously with emplacement, with the result that amphibolite grade rocks were brought up from lower depths and juxtaposed with metavolcanic rocks in a fault contact. Faulting apparently continued after emplacement of the plutons, as evidenced by pervasive cataclastic foliations in the plutons.

Three separate events followed the main phases of deformation: (1) intrusion of mafic units into older rocks in the area (during Upper Precambrian time?), with the units trending subparallel to the major boundary fault, (2) the introduction of quartz veins into these and associated units, and the local greenschist facies metamorphism of the mafic rocks, and (3) local minor faulting of the quartz veins and their host rocks.

SUMMARY AND CONCLUSIONS

The structure and petrology of the Precambrian metamorphic units in northwestern Marathon County indicate two deformational phases accompanied by varying degrees of recrystallization. The two deformations are: (1) amphibolite grade metamorphism of pre-existing rocks in the gneissic terrane, greenschist facies metamorphism of volcanic rocks, and the development of a similar foliation and lineation trend in both terranes; and (2) the cataclastic deformation of gneissic and metavolcanic rocks within and near to the boundary fault zone, and the development of two major joint systems.

Amphibolite facies metamorphism occurred under moderate to high temperature-pressure conditions. Petrologic evidence for this includes quartzofeldspathic and mafic mineral assemblages in the gneissic terrane diagnostic of amphibolite facies metamorphism. Textural relationships in the gneisses indicate disequilibrium conditions during recrystallization, while locally conditions approached textural equilibrium. The presence of migmatites and complex folds is further evidence for regional metamorphism involving deformation at high temperatures and pressures.

The gneisses exhibit a consistent regional orientation of both foliation and lineation, with foliation planes dipping 70° north with an average strike of N79°E, and lineations plunging 70° to the northwest in the plane of foliation. Fold axes plunge westerly at 47° to 78°.

The volcanic rocks in the study area were metamorphosed to greenschist facies. Where the rocks are not highly deformed primary volcanic textures and structures are well preserved. The volcanic rocks exhibit structures similar to those in the gneissic terrane. Foliations dip 65° to the north with an average strike of N71°E, while lineations have an average plunge of 65° to the northwest in the plane of foliation. Local fold axes in the metavolcanic terrane plunge westerly at 17° to 88°.

The similarity of penetrative structures in both terranes, combined with strain analysis results, indicate a strain history in the study area such that maximum elongation (extension) occurred parallel with lineation in the plane of foliation, while shortening (flattening) occurred in a northwest-southeast direction, perpendicular to foliation. Strain analyses also indicates the rocks were shortened up to 40 percent of their original length.

The second deformational phase is defined by the presence of cataclastic rocks derived from both terranes, slickenside surfaces, the local development of a linear fabric associated with cataclasis, and the development of two major joint systems. The major joint system trends northwest-southeast, perpendicular to foliation, while a second major system trends northeast-southwest, parallel with foliation. If these joint sets are tensional features, the stress field which caused their development would be consistent with the stress field which developed the foliation during the first deformational phase.

Shearing along the major boundary zone between the two terranes was probably intermittently active for a period of time. Faulting may have been the mechanism responsible for bringing the amphibolite grade rocks up from lower depths in the earth's crust. It may have been at this time that both gneissic and volcanic rocks were cataclastically deformed along and near to the boundary zone.

Granitic to tonalitic plutonic rocks intruded both terranes, about 1840 m.y. ago. Dynamic deformation continued after the emplacement of these rocks, as seen by pervasive cataclastic foliations.

The next event in the area was the emplacement and local metamorphism to greenschist facies of mafic units. These rocks intrude the volcanic terrane and trend subparallel to the major boundary fault. Following this, minor quartz veins cut these and other rocks in the area. The last recorded event was the local faulting of the quartz veins and their host rocks.

The petrologic and structural evidence in northwestern Marathon County define a high-grade metamorphic complex which is lithologically distinct and tectonically separate from a lower-grade suprastructure. The contact between the two terranes is defined by a relatively thin boundary zone having a metamorphic gradient with complex shearing.

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APPENDIX I

LOCATION OF SAMPLES

HAM:	1-1	SW¼SW¼NW¼	SEC 9	T29N	R5E
HAM:	1-2	SW¼SW¼NW¼	SEC 9	T29N	R5E
HAM:	2-1	NW¼SW¼NW¼	SEC 9	T29N	R5E
HAM:	2-2	NW¼SW¼NW¼	SEC 9	T29N	R5E
HAM:	2-3	NW¼SW¼NW¼	SEC 9	T29N	R5E
HAM:	3-1	SE¼NW¼SE¼	SEC 5	T29N	R5E
ATH:	49-1	NW¼SE¼SW¼	SEC 32	T29N	R4E
ATH:	50-1	SW¼SW¼	SEC 1	T29N	R3E
ATH:	50-2	SW¼SW¼	SEC 1	T29N	R3E
ATH:	50-3	SW¼SW¼	SEC 1	T29N	R3E
ATH:	50-4	SW¼SW¼	SEC 1	T29N	R3E
ATH:	50-5	SW¼SW¼	SEC 1	T29N	R3E
ATH:	50-6	SW¼SW¼	SEC 1	T29N	R3E
ATH:	50-7	SW¼SW¼	SEC 1	T29N	R3E
ATH:	50-8	SW¼SW¼	SEC 1	T29N	R3E
ATH:	50-9	SW¼SW¼	SEC 1	T29N	R3E
ATH:	50-10	SW¼SW¼	SEC 1	T29N	R3E
ATH:	50-11	SW¼SW¼	SEC 1	T29N	R3E
ATH:	51-1	NW¼NW¼SW¼	SEC 6	T29N	R4E
ATH:	51-2	NW¼NW¼SW¼	SEC 6	T29N	R4E
ATH:	51-3	NW¼NW¼SW¼	SEC 6	T29N	R4E
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ATH:	51-5	NW¼NE¼SW¼	SEC 6	T29N	R4E
ATH:	51-6	NW¼NE¼SW¼	SEC 6	T29N	R4E
ATH:	51-12	NE¼NW¼SW¼	SEC 6	T29N	R4E
ATH:	51-13	NE¼NW¼SW¼	SEC 6	T29N	R4E
ATH:	51-14	NE¼NW¼SW¼	SEC 6	T29N	R4E
ATH:	52-1	SW¼NE¼SW¼	SEC 31	T30N	R4E
ATH:	52-2	SW¼NE¼SW¼	SEC 31	T30N	R4E
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ATH:	52-16	NW¼SE¼SW¼	SEC 31	T30N	R4E
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ATH:	55-3	NE¼SE¼	SEC 25	T30N	R4E
ATH:	55-4	N½SW¼SE¼	SEC 3	T29N	R4E
ATH:	55-5	NW¼SE¼NW¼	SEC 26	T30N	R3E
ATH:	55-6	SE¼SW¼	SEC 22	T30N	R3E
ATH:	55-7	NW¼NW¼SW¼	SEC 22	T30N	R3E
ATH:	55-8	NW¼NW¼SW¼	SEC 22	T30N	R3E
ATH:	56-1	NW¼SW¼NW¼	SEC 33	T30N	R4E
ATH:	56-2	NW¼SW¼NW¼	SEC 33	T30N	R4E
ATH:	56-3	NW¼SW¼NW¼	SEC 33	T30N	R4E
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ATH:	58-5	SE¼NW¼	SEC 10	T29N	R4E
ATH:	58-6	SE¼NW¼	SEC 10	T29N	R4E
ATH:	58-7	SE¼NW¼	SEC 10	T29N	R4E
ATH:	58-8	SE¼NW¼	SEC 10	T29N	R4E
ATH:	58-9	SE¼NW¼	SEC 10	T29N	R4E
ATH:	58-10	NW¼SE¼NW¼	SEC 10	T29N	R4E
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ATH:	58-13	NW¼NW¼SW¼	SEC 10	T29N	R4E
ATH:	58-14	NW¼NW¼SW¼	SEC 10	T29N	R4E
ATH:	58-15	NW¼NW¼SW¼	SEC 10	T29N	R4E

ATH:	58-16	NW¼NW¼SW¼	SEC	10	T29N	R4E
ATH:	58-17	NW¼NW¼SW¼	SEC	10	T29N	R4E
ATH:	58-18	SW¼SW¼SE¼	SEC	9	T29N	R4E
ATH:	58-19	NE¼NE¼NW¼	SEC	16	T29N	R4E
ATH:	58-20	NE¼NE¼NW¼	SEC	16	T29N	R4E
ATH:	59-1	SW¼SW¼NW¼	SEC	3	T29N	R4E
ATH:	59-2	SW¼SW¼NW¼	SEC	3	T29N	R4E
ATH:	59-3	S½NE¼SW¼	SEC	3	T29N	R4E
ATH:	59-4	S½NE¼SW¼	SEC	3	T29N	R4E
ATH:	59-5	SW¼NW¼SE¼	SEC	3	T29N	R4E
ATH:	59-6	NE¼SW¼SE¼	SEC	3	T29N	R4E
ATH:	59-7	SE¼NE¼SE¼	SEC	3	T29N	R4E
ATH:	59-8	S½	SEC	2	T29N	R4E
ATH:	60-1	SE¼NW¼SW¼	SEC	11	T30N	R4E
ATH:	60-2	SE¼NW¼SW¼	SEC	11	T30N	R4E
ATH:	61-1	NW¼NW¼NE¼	SEC	10	T30N	R4E
LIN:	1-1	SW¼SW¼	SEC	29	T31N	R4E
LIN:	1-2	SE¼SE¼SE¼	SEC	30	T31N	R4E
LIN:	1-3	SW¼NE¼NE¼	SEC	31	T31N	R4E
LIN:	2-1	SE¼SW¼	SEC	31	T31N	R4E
LIN:	2-2	SE¼SW¼	SEC	31	T31N	R4E
HAM:	6-1	NW¼SE¼	SEC	13	T30N	R4E
TAY:	1-1	NE¼SW¼NE¼	SEC	25	T31N	R3E
TAY:	1-2	SE¼NE¼	SEC	25	T31N	R3E
TAY:	1-3	SE¼NE¼	SEC	25	T31N	R3E
TAY:	1-4	SE¼NE¼	SEC	25	T31N	R3E
TAY:	1-5	NE¼SW¼NE¼	SEC	25	T31N	R3E
TAY:	1-6	NE¼SW¼NE¼	SEC	25	T31N	R3E
TAY:	1-7	SE¼NW¼NE¼	SEC	25	T31N	R3E
TAY:	1-8	NE¼SW¼NE¼	SEC	25	T31N	R3E
TAY:	1-9	NW¼SE¼NE¼	SEC	25	T31N	R3E
TAY:	1-10	SE¼NE¼	SEC	25	T31N	R3E
TAY:	1-11	SE¼NE¼	SEC	25	T31N	R3E
TAY:	1-12	SE¼NE¼	SEC	25	T31N	R3E
TAY:	1-13	SE¼SE¼NE¼	SEC	25	T31N	R3E
TAY:	1-14	SE¼SE¼NE¼	SEC	25	T31N	R3E
TAY:	1-15	SE¼SE¼NE¼	SEC	25	T31N	R3E
TAY:	1-16	SE¼SE¼NE¼	SEC	25	T31N	R3E

APPENDIX II

OPERATIONAL DEFINITIONS

Metamorphic Rocks

Metamorphic rocks within the present area of study were classified megascopically as defined below. Cataclastic rocks, although metamorphic, will be discussed separately.

Textural Terminology

With preferred orientation

aphanitic, slaty cleavage.	slate
intermediate between slate and schist.	phyllite
phaneritic, schistose.	schist
phaneritic, gneissic	gneiss

Without preferred orientation

aphanitic-phaneritic, granoblastic.	granofels

Compositional Terminology

mafic; Na-plagioclase, epidote, chlorite	greenstone
mafic; plagioclase and amphibole. . .	amphibolite
"mixed gneiss", part granitic, part more mafic.	migmatite

To the above general rock names, the dominant minerals and special textures found in each rock were prefixed. In addition, in cases where the nature of the protolith was obvious, the prefix "meta-" was used (eg., meta-diabase).

Cataclastic Rocks

Cataclastic rocks within the present area of study were classified according to Table 5. Cataclastic

Table 5. Classification used in this study for cataclastic rocks (after Higgins, 1971).

Approximate volume percent porphyroclasts in rocks with fluxion structure or Approximate volume percent fragments in rocks without fluxion structure.	ROCKS WITH PRIMARY COHESION — Cataclasis dominant over neomineralization-recrystallization: ROCKS WITHOUT FLUXION STRUCTURE	Cataclasis dominant over neomineralization-recrystallization: ROCKS WITH FLUXION STRUCTURE		Neomineralization-recrystallization dominant over cataclasis: ROCKS WITH FLUXION STRUCTURE	Approximate size of most porphyroclasts in rocks with fluxion structure or Approximate size of most fragments in rocks without fluxion structure.
>50	Microbreccia	Protomylonite		Mylonite Gneiss (mylonite schist)	Visible to naked eye
<50 – 30	Microbreccia	Mylonite	Phyllonite (variety)	Mylonite Gneiss (mylonite schist)	Visible to naked eye
30 – >10	Cataclasite	Mylonite	Phyllonite (variety)	Blastomylonite	> 0.2 mm
<10	Cataclasite	Ultramylonite	Phyllonite (variety)	Blastomylonite	< 0.2 mm

All rocks are gradational.

Approximate volume percent porphyroclasts in rocks with fluxion structure or Approximate volume percent fragments in rocks without fluxion structure.

Approximate size of most porphyroclasts in rocks with fluxion structure or Approximate size of most fragments in rocks without fluxion structure.

rocks with primary cohesion are basically metamorphic rocks and owe their cohesion to a combination of crystalloblastic and cataclastic processes (Higgins, 1971). Cataclastic rocks were classified quantitatively by using approximate size of most of the porphyroclasts or fragments, combined with approximate percentage of these features.

In outcrop and hand sample cataclastic rocks may be easily mistaken for metasedimentary, metavolcanic, volcanic, or fine-grained intrusive rocks. Parent rock types are recognizable where the rocks are only slightly sheared; however, more severe cataclasis makes it virtually impossible to determine the original rock type. This has presented problems in determining lithologic boundaries during the mapping.

Several cataclastic terms with which the reader may be unfamiliar are listed below (after Higgins, 1971):

cataclasis: The process by which rocks are broken and granulated due to stress and movement during faulting; granulation or comminution.

color lamination: Layering due to color differences, regardless of origin, in adjacent layers of rock, whether on a megascopic or microscopic scale.

comminution: Reduction in size of the constituents of a rock due to cataclasis.

compositional layering: Layering due to chemical and mineralogical differences in the adjacent layers, regardless of origin. May include color lamination.

crystalloblastic texture: A crystalline texture due to metamorphic growth of minerals in solid rocks by recrystallization and/or neomineralization. In this texture the essential constituents have crystallized simultaneously and not in sequence. A constructive texture as opposed to cataclastic texture which is chiefly destructive.

fluxion structure: Cataclastically produced directed penetrative texture or structure commonly involving a family or set of s-surfaces; cataclastic foliation. May be visible megascopically or only microscopically. Does not necessarily involve compositional layering or lamination, although many examples do show such layering.

mortar: Refers to fine-grained rock powder between porphyroclasts or within shears in a rock; like mortar between stones or bricks.

mortar structure (mortar texture): Refers to a structure or texture in rocks characterized by mortar between and around porphyroclasts, or filling shears between unground fragments of the rock.

neomineralization: The process of metamorphic transformation of the old mineral constituents of a rock into new minerals of different composition; new mineral growth.

porphyroblast: A relatively large crystal or mineral grain developed during metamorphism by neomineralization and/or recrystallization. Porphyroblasts are larger than the matrix which encloses them.

porphyroclast: A relatively large fragment of a crystal, mineral grain, or aggregate of crystals or grains, in a cataclastic rock. Porphyroclasts are not produced by neomineralization or recrystallization (as opposed to porphyroblasts), but may be recrystallized in blastomylonites and mylonite gneisses.

primary cohestion: Refers to congenital coherence of a rock, as opposed to that produced by secondary cementation. Essentially metamorphic cohesion.

recrystallization: Metamorphic crystallization of new mineral grains from old minerals of the same chemical constitution (for example, quartz from quartz); as opposed to neomineralization.

shear zone: A zone of shearing in rocks; essentially like a fault zone, but more specific because it excludes zones of faulting not associated with shear.

Igneous Rocks

Igneous rocks within the area of study were classified according to Table 6. In addition, several igneous terms which are used in this paper are defined below. They include:

agglomerate: A pyroclastic rock that consists of angular volcanic fragments and/or non-volcanic fragments in a volcanic matrix. The fragments in both cases are greater than 2.0 mm in diameter.

anorthosite: A variety of gabbro in which greater than 80 percent of the rock is calcic plagioclase.

diabase: A relatively fine-grained gabbro which usually has an ophitic texture and random plagioclase laths.

glomeroporphyritic: Refers to phenocrysts occurring in clusters.

tuff: Lithified volcanic ash 0.25 to 4.0 mm in diameter.

Table 6. Classification used in this study for igneous rocks (after Green, 1970).

Ratio of Feldspars	Alkali Feldspar Predominant (> 2/3 of fsp)		Two Feldspars about equal		Plagioclase Predominant (> 2/3 of fsp)		Only Plagioclase			
							Sodic An_{1-49}		Calcic An_{50-100}	
Mafics	Biotite and/or Hornblende increasing		Muscovite						Pyroxene, Olivine	
Quartz	> 10% Qz	< 10% Qz	> 10% Qz	< 10% Qz	> 10% Qz	< 10% Qz	> 10% Qz	< 10% Qz	Qz	No Qz
Texture:										
Phaneritic	GRANITE	Syenite	ADAMELLITE (Quartz Monzonite)	Monzonite	GRANODIORITE	Syenodiorite	TONALITE (Quartz Diorite)	DIORITE	Quartz Gabbro	GABBRO
Aphanitic	RHYOLITE	Trachyte	DELLENITE (Quartz Latite)	Latite	RHYODACITE	Trachyandesite	DACITE	ANDESITE	Quartz Basalt	BASALT