PETROLOGY AND STRUCTURE OF
PRECAMBRIAN GNEISSES AT HOLCOMBE,
CHIPPEWA COUNTY, WISCONSIN

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
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BY
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AMPHIBOLITE, SYNKINEMATIC INTRUSIVES AND AMPHIBOLITE SCHIST CROP OUT ALONG THE CHIPPEWA AND FISHER RIVERS, NEAR HOLCOMBE, IN CHIPPEWA COUNTY, WISCONSIN. THESE ROCK FORMATIONS OCCUR NEAR THE NORTHERN BOUNDARY OF AN ARCHEAN (?) TERRANE OF AMPHIBOLITIC GNEISES AND SCHISTS KNOWN AS THE CHIPPEWA AMPHIBOLITE COMPLEX. TO THE NORTH OF THE CHIPPEWA COMPLEX LIES THE MIDDLE PRECAMBRIAN FLAMBEAU PROVINCE, COMPOSED OF INTERMEDIATE TO FELSC VOLCANICS AND METASEDIGMENTS.

THREE MAJOR ROCK UNITS ARE EXPOSED NEAR HOLCOMBE. FROM OLDEST TO YOUNGEST THESE ARE: INTERBANDED AMPHIBOLITE GNEISS AND TONALITE AT THE FISHER RIVER, QUARTZ DIORITE GNEISS AND ASSOCIATED META-IGNEOUS ROCKS AT HOLCOMBE DAM, AND AMPHIBOLITE SCHIST ALONG THE CHIPPEWA RIVER. INTRUSIVES INTO THE QUARTZ DIORITE INCLUDE MEDIUM-GRAINED GRANITE AND GRANITE DIKES, AND A HYPAHYSSAL ANDESITE INTRUSIVE.

BANDED GNEISS AT THE FISHER RIVER DISPLAYS THREE PERIODS OF FOLDING. DURING THE FIRST PHASE OF DEFORMATION, ISOCLINAL FOLDS, F₁, WERE PRODUCED IN INTRUSIVE TONALITE VEINS, AS WELL AS FOLD AXIS AND MINERAL LINEATIONS, L₁. A DOMINANTLY EAST-WEST, VERTICALLY DIPPING MINERAL FOLIATION, S₁, WAS ALSO PRODUCED. DURING F₁ A LITHOLOGIC LAYERING OF TONALITE WITH AMPHIBOLITE WAS FORMED IN SELECTED ZONES PROBABLY DURING TRANPOSITION OF AN ORIGINAL S₀ SURFACE OF TONALITE TO S₁ AND SUBSEQUENT SHEARING.

EXTENSIVE RECRYSTALLIZATION IN THE LOWER AMPHIBOLITE FACIES
occurred during the \( F_1 \) event. Continued recrystallization after \( F_1 \) produced garnets in biotite rich zones of the banded gneiss.

\( F_2 \) deformation produced tight to isoclinal folds which refolded \( L_1 \) lineations along a great circle distribution. \( F_2 \) folds trend east-northeast at an oblique angle to \( F_1 \) folds and plunge moderately to steeply west.

A third fold deformation, \( F_3 \), produced broad, open folds along a steeply dipping north-south axis.

At Holcombe Dam, \( S_1 \) foliation, and \( F_2 \) and \( F_3 \) folds can be observed in the quartz diorite gneiss. The quartz diorite was intruded and partially metamorphosed to the lower amphibolite facies during \( F_1 \).

Granite intrusives and the hypabyssal andesite display faint east-northeast foliations and steep to moderate westerly plunging lineations, suggesting that these two units were intruded during the \( F_2 \) event. These units were partially metamorphosed to the amphibolite facies during \( F_2 \).

After folding, an extensive period of shearing affected the quartz diorite gneiss and intrusives. A series of small shear zones formed in the gneiss. These trend N70E and have moderate to steep westerly plunging lineations.

The amphibolite schist displays all the same structural characteristics as small shear zones in the quartz diorite gneiss, and is therefore interpreted to represent a major shear zone which crosscuts the area. Average modal compositions of the amphibolite schist suggest that the protolith was an
igneous rock of dioritic composition.

Final phases of deformation produced brittle faulting throughout the area. A set of faults trending N50W and N20W offset all other structural features in the area.

Structures in the area closely resemble those produced by the Penokean event in the region.
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Last, but not least, the author would like to thank God that the end is in sight.
INTRODUCTION

The area of study is located near the town of Holcombe, Wisconsin, in northeastern Chippewa County in Township 32 North, Range 6 West, and including sections 27, 28, 29 and parts of 32, 33 and 34. Fewer than twenty outcrops are known in this area. Half of those lie along the banks of or within the Chippewa River, and the others lie to the east along the Fisher River.

The Holcombe area is situated at or near the northern boundary of an extensive terrane of amphibolitic gneisses and schists, which is informally named the "Chippewa Amphibolite Complex" (Myers, 1974 - see Figure 1). To the north of the Chippewa Complex lies the "Flambeau Volcanic-sedimentary Province," consisting of a belt of intermediate to felsic volcanics and metasediments. A major crustal break called the Jump River Fault is postulated to form the boundary between these two terranes (Sims et al., 1978).

Regional Geology

Massive banded amphibolite gneisses and schists are the dominant rock types of the Chippewa Amphibolite Complex. Amphibolites are distributed as interlensing units with the granitic units at near-vertical shear zones (Myers, 1974). The mineral assemblage plagioclase-hornblende is ubiquitous, and quartz, biotite, garnet and cummingtonite are also common.

All of the amphibolitic rocks in the region display
Figure 1. General geology of Eau Claire and Chippewa counties.
penetrative deformation in the form of compositional layering, schistosity and lineations. Folding, boudinage and shearing are locally common. Major structural trends strike west-northwest in the southern part of the complex, and east-northeast in the northern sections.

Mafic and ultramafic rocks occur both as inclusions in amphibolitic rocks and as intrusives into granitic rocks. Pyroxene gabbro, pyroxenite and anorthosite are the most common compositional types. The youngest mafic intrusives in the region occur in the form of diabase dikes.

The amphibolitic gneisses in west-central Wisconsin have not been radiometrically dated. A gabbro intrusive at Little Falls in Eau Claire county has tentatively been dated at 1900 m.y. by W. R. Van Schmus (Myers, 1974). This gabbro is undeformed and intrudes strongly deformed amphibolitic rocks.

The Flambeau Province consists dominantly of rhyolitic and andesitic lithic or crystal tuffs, and rhyodacite to dacite volcanioclastics, as well as sedimentary graphite schists, quartzites and pelitic rocks (Myers, 1974). Mafic volcanic rocks are exposed along the Jump River. Although rocks in the Flambeau Province have not been dated, model lead ages from volcanogenic massive sulfides in the province suggest that the rocks are Middle Precambrian in age (Sims, 1976). Most of the rocks in the Flambeau Province have been metamorphosed to the greenschist facies, but pelitic rocks which reach the staurolite grade have been reported (May, 1977). Although
no detailed work on the structure of the region exists, the rocks are steeply dipping and appear to be isoclinally folded.

The rocks, both of the Chippewa Complex and the Flambeau Province, have been intruded by granitic rocks of several relative ages. The intrusives range from trondhjemite to granite in composition. These intrusive events are often associated with a set of pegmatite dikes. Textures range from typically igneous to strongly gneissic.

The existence of the Jump River fault is hypothetical and is based on major magnetic and gravity anomalies which trend across the region. The Jump River Fault is postulated to lie along part of the boundary between the Chippewa Complex and the Flambeau Province.

Cambrian sandstones were deposited unconformably on Precambrian rocks after a prolonged period of weathering. The Upper Cambrian Mount Simon and Eau Claire Formations form the dominant rock units west of the area. No Cambrian outcrops occur within the area of study, but Cambrian outliers occur within a ten mile radius of the Holcombe area.

Precambrian and Cambrian rocks in the region are covered with glacial drift varying from ten to one hundred feet or more in thickness. The glacial material was deposited during resurgence of the Wisconsin age Chippewa Lobe. Ground moraine to the east of the Holcombe-Cornell area is replaced by outwash material at Holcombe and south. Many rivers in the region have cut through the drift, exposing Cambrian and Precambrian basement rocks.
Previous Works

Little previous work has been done on the geology of western Wisconsin, and a comprehensive synthesis is not available. The earliest work done in the region was carried out by the Wisconsin Geological Survey in an attempt to evaluate mineral resources in northern Wisconsin (summarized in Geology of Wisconsin, 1879). Dip needle surveys were implemented in surrounding counties, but no work was done in Chippewa county. In 1972, regional reconnaissance mapping and petrologic studies of Eau Claire and Chippewa counties were begun by Paul Myers and students at the University of Wisconsin - Eau Claire (in preparation). Among other studies is a synthesis of the deformational history of rocks at Jim Falls by Maerklein (1974). Petrologic and structural studies of the Big Falls area in Eau Claire county were completed by Cummings (1975). In Fall of 1974, the 38th Tri-State Geologic Field Conference was held in Eau Claire, field trips were taken to the Precambrian rocks of Eau Claire and Chippewa counties, and a guidebook was prepared for the area (Myers, 1974). A second field trip was held in spring, 1977, which covered areas in the Chippewa Amphibolite Complex and into the "Black River Province" to the south (Myers, 1977).

Statement of Purpose

Little has been done, and little is known about the geology of western Wisconsin. This study is an attempt to describe and interpret the geologic history of gneisses exposed at the northern edge of a major gneiss belt in the hope
of attaining useful insights into the regional geology and specifically the nature of this boundary. Emphasis will be placed on the study of relationships between the deformational and metamorphic histories of the region based on field and petrologic studies.

**Methods**

Approximately four weeks were spent mapping the Holcombe area and collecting samples. Detailed outcrop maps on the scale of 1 inch to 10 feet or 1 inch to 20 feet were made of several of the major outcrops for the purpose of delineating the detailed structure. A total of 250 foliations, 60 lineations and 185 fault and fracture surface were measured from the three major units.

Petrologic study was done on 128 thin sections and all rocks were stained for calcium and potassium. Ten thin sections were similarly stained in order to distinguish untwinned or highly deformed or altered plagioclase from microcline or quartz.
FIELD RELATIONS AND PETROLOGY

Three major areas of outcrop occur at Holcombe, Wisconsin and each is dominated by a major rock unit. From oldest to youngest, these are: banded gneiss at the Fisher River, quartz diorite and intrusives at Holcombe Dam, and amphibolite schist along the Chippewa River. A geologic map showing the outcrop distribution of these units is shown in Figure 2.

No contacts between the major units were exposed and the relative ages were determined on the basis of structural and field evidence presented in the following chapters. The field relations and petrology of each of the major units will be discussed separately below.

Banded Gneiss along the Fisher River

The banded gneiss exposed along the Fisher River consists of a host amphibolite unit with bands and veins of coarse-grained tonalite (Figure 3). The amphibolite displays a wide variety of textures based on variation of grain size and relative amounts of hornblende and plagioclase and is interpreted to represent a breccia composed dominantly of volcanic clasts. Mafic clasts are flattened along the plane of foliation. A few pale green clasts represent fragments of a metamorphosed calcareous rock (Figure 4).

Tonalite occurs mostly as large, coarse-grained bands in the amphibolite, concordant to foliation, or as numerous, small crosscutting, medium-grained intrusive veins. Much of the tonalite banding is tectonic in origin (see discussion of
Figure 2. Geologic map of the Holcombe area. Black dots are outcrops. qd - quartz diorite gneiss, ams - amphibolite schist, bgn - banded gneiss.
Figure 3. Banded gneiss at the Fisher River

Figure 4. Pale green calcareous clast in the amphibolite at the Fisher River.
Amphibolite The amphibolite is composed dominantly of plagioclase (31-78%) and hornblende (20-50%) with lesser amounts of quartz and biotite, and more rarely, garnet. See Table 1. Epidote, sphene, apatite, pyrite, magnetite and ilmenite occur in minor amounts. Textures vary from granular to finely schistose.

Plagioclase is generally anhedral to subhedral with granular textures dominating. Where it has a lath like or tabular form, plagioclase is foliated. Albite and pericline twinning, and normal zoning are common. Plagioclase compositions estimated by the Michel-Levy method range from An$_{52}$-An$_{65}$ (labradorite).

In one clast, containing 78% plagioclase, clots of subhedral plagioclase to 3 mm in size were foliated in a matrix of fine-grained (0.3 mm) plagioclase. This may be a relict volcanic texture from a clast which had phenocrysts of plagioclase.

Hornblende is pleochroic with $\alpha$ straw yellow, $\beta$ olive green and $\gamma$ blue green, $2V$ is approximately $85^\circ$ and $\gamma A c$ is $15^\circ - 18^\circ$. It most often occurs in medium-grained granular aggregates with plagioclase (Figure 5) or as decussate aggregates in bands and clots. In a few places it forms a schistose fabric of parallel prisms. A few grains have inclusions of quartz and plagioclase. The average size is generally less than 1 mm, but may average 1-3 mm in hornblende-rich bands.

Biotite is generally red brown and pleochroic. It occurs
Table 1. Modal analyses of samples from banded gneiss at the Fisher River.

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intergrown with hornblende or as individual flakes, and is foliated. Sometimes it is partially altered to chlorite.

In a few places, narrow zones of biotite schist occur along the edges of tonalite veins, probably as the result of shearing. Garnets sometimes occur in these biotite-rich zones. These are pale red in hand sample. In thin section, they are anhedral and show retrograde metamorphism to chlorite and epidote. See Figure 6. A few have overgrown the $S_1$ foliation in one place, and foliation in the limb of a minor $F_2$ fold wraps around garnet, placing the formation of garnet after the $F_1$ and before the $F_2$ fold events (see Structure).

Clinopyroxene was found in one sample from a small outcrop near Highway 27, south of the Fisher River. It is pale green to colorless with positive $2V$ approximately $65^\circ$. It has a blocky habit and is usually rimmed with blue green hornblende, which overgrows pyroxene grains in optical continuity.

The amphibolite unit is generally unaltered except for minor calcite and chlorite. Infrequently, lenses and patches of epidote a few centimeters long occur as wholesale replacement of plagioclase.

A few calcareous clasts occur in the amphibolite unit. These are composed dominantly of anhedral, poikiloblastic epidote and diopside with lesser amounts of quartz and calcite, and a trace of garnet. This assemblage is similar to that of metamorphosed siliceous dolomites from the almandine zone of the Scottish Highlands originally mapped by Barrow (1893).

Spotted mafic dikes The amphibolite unit is cut by
Figure 5. Granular texture in amphibolite at the Fisher River. Field of view is 6 mm. Sample number MY71C.

Figure 6. Anhedral garnet formed near boundary between biotite schist and vein of tonalite, from the banded gneiss at the Fisher River. Field of view is 6 mm. Sample number MG710.
spotted mafic dikes composed of 58-72% hornblende and 26-35% plagioclase with lesser amounts of biotite (to 6%) and quartz (1%) with minor epidote, chlorite and opaques. Clots of hornblende, which reach 3 mm in size occur in a fine-grained granular matrix of plagioclase and hornblende. Hornblende clots are both foliated and lineated. A few are pseudomorphs of pyroxene (Figure 7). Hornblende and biotite in the matrix are also foliated.

**Tonalite** The tonalite bands and intrusive veins are composed of plagioclase (44-58%) and quartz (23-44%) with lesser biotite (4-11%) and minor amounts of epidote, allanite

Figure 7. Hornblende pseudomorph after pyroxene in spotted mafic dike at the Fisher River. Field of view is 6 mm. Sample number MG74-F
zircon, sphene and opaques, as well as secondary calcite and chlorite.

Plagioclase forms subhedral and euhedral blocky prisms ranging from 15 mm - 1 cm in size (Figure 8). Compositions range from An$_{57}$ - An$_{62}$. Many grains are deformed, and display bent twins, deformation twinning, microfracturing and polygonization. Small (less than 0.5 mm) recrystallized grains of plagioclase occasionally form along cracks or around the edges of larger plagioclase grains. Slight alteration to muscovite or saussurite is common.

Recrystallized quartz forms the matrix for the plagioclase. Anhedral grains reach 3 mm in size and generally have irregular boundaries. Most quartz has undulatory extinction or deformation banding.

Brown biotite occurs in stringers, wrapping around plagioclase grains or as individual foliated grains. Biotite sometimes grows along fractures in plagioclase grains. It is undeformed, and is sometimes replaced by chlorite with anomalous purple interference colors. Minor sphene is usually associated with the chlorite.

Zircon occurs as euhedral grains to 0.5 mm. Zoned grains with one overgrowth have been observed.

Euhedral allanite is a common minor mineral in the tonalite. It is nearly always metamict and is often rimmed by radial growths of epidote (Figure 9).

Interpretation

The protolith of the amphibolite at the Fisher River is
Figure 8. Euhedral prisms of plagioclase in quartz matrix, tonalite at the Fisher River. Field of view is 6 mm. Sample number MG75-F.

Figure 9. Euhedral allanite with radial rim of epidote in tonalite at the Fisher River. Field of view is 6 mm. Sample number MG75-P.
a breccia composed mostly of volcanic clasts dominantly of basaltic composition, with a few clasts of a calcareous rock. It was metamorphosed to the amphibolite facies during $F_1$ deformation, causing a preferred orientation, especially of mafic minerals. Continued metamorphism after deformation formed garnets, overgrowing the $S_1$ foliation. A second recrystallization, after the second fold deformation, $F_2$, recrystallized mafic minerals in $F_2$ folds around the garnets. The clinopyroxene found in one amphibolite sample could be a relict mineral from the original igneous rock.

Coarse-grained tonalite banding was formed in the rock during the $F_1$ fold deformation. Most of the tonalite banding is tectonic in origin, although the medium-grained veins and a few crosscutting pods of coarse tonalite are intrusive. Large euhedral plagioclase grains are deformed, and may be relict igneous grains. Minor recrystallization of plagioclase along with crystallization of quartz and biotite occurred during $F_1$.

Late crystallization of epidote and muscovite, mostly as alteration products of plagioclase occurred in both rock types.

Quartz Diorite and Associated Intrusives at Holcombe Dam

Gneissic quartz diorite and associated meta-igneous rocks are exposed below Holcombe Dam. In order of decreasing relative age, the latter are: ultramafic and mafic xenoliths in the quartz diorite, quartz diorite gneiss, granite and associated granite dikes, and hornblende andesite. See Plate 1. These units were converted to schist along shear zones which cross-cut the outcrop area. Each of these rock types and the shear
zones will be described separately below.

**Inclusions**

The quartz diorite unit contains two types of inclusions: hornblende rich ultramafic inclusions, and spotted mafic inclusions.

**Ultramafic inclusions** Ultramafic inclusions occur only along the northwest portion of the exposed quartz diorite. See Figure 10. The ultramafic inclusions are generally less than 0.5 meter in length, although at least one is almost 2 meters long. The smaller inclusions weather more rapidly than the host quartz diorite, and small pits remain where they are weathered out. They are composed of 75-85% hornblende, 11-13% biotite with a small amount of interstitial plagioclase. Chlorite, as an alteration of biotite and less commonly of hornblende, can compose more than 20% of the rock.

Hornblende in the ultramafic inclusions forms a felty mass of intertwining fibers 0.8 to 3 mm long (Figure 11). It is pleochroic with $\alpha$ tan, $\beta$ pale green and $\gamma$ pale blue green. $2V$ is about $85^0$ and $\gamma A c = 15^0$. A few hornblende grains contain fine needles of ilmenite oriented along cleavage planes, especially concentrated in the cores of grains. Many samples have a spaced schistosity in zones 2 to 5 mm apart. Schistose zones are less than 2 mm wide and contain greater amounts of biotite and chlorite than the surrounding rock.

In a few places where the inclusions have been sheared, hornblende is bent and shows undulatory extinction or is polygonized. More often, the deformation of hornblende is
Figure 10. Ultramafic inclusions in quartz diorite gneiss at Holcombe Dam. Ruler is 0.5 meter long.

Figure 11. Felty hornblende from ultramafic inclusion. Field of view is 6 mm. Sample number GN613.
controlled by its strong cleavage, and grains are broken up and sheared apart along cleavage planes.

In one sample taken from the center of the large inclusion previously mentioned, hornblende was partly altered to chlorite and actinolite. Hornblende grains are rimmed by small felty laths of actinolite or actinolite rims hornblende in optical continuity. This retrograde metamorphism may have occurred during the intrusion of quartz diorite.

**Spotted mafic inclusions** Spotted mafic inclusions are similar in texture to the spotted mafic dikes at the Fisher River (Figure 12). The fact that they occur as inclusions at Holcombe Dam suggests that the quartz diorite is younger than the amphibolite unit at the Fisher River.

The spotted inclusions occur along the southeast section of the exposed quartz diorite. They range from a few centimeters across to 6 meters in length. They are often surrounded by a white rind a few centimeters wide, consisting of plagioclase and quartz. In thin section, these rinds have a texture similar to that of the quartz diorite except that mafic minerals are lacking. Their existence is probably the result of preferential nucleation of plagioclase on the inclusions during the intrusion of the quartz diorite.

The spotted mafic inclusions differ from dikes at the Fisher River in that they contain relict phenocrysts of subhedral plagioclase in the matrix. These reach 4 mm in size and contain numerous inclusions of hornblende and biotite, especially around their borders.
Figure 12. Hornblende clot in spotted mafic inclusion in the quartz diorite gneiss. Field of view is 6 mm, uncrossed polars. Sample number GN634.

Quartz Diorite Gneiss

The quartz diorite is a medium-grained, dark to medium gray rock with rusty weathering surfaces. It is faintly foliated and has white discontinuous bands and lenticles which are more quartz rich than the rest of the rock.

The quartz diorite is composed mostly of plagioclase (32-51%), quartz (11-31%) and mafic minerals (12-33%). See Table 2. Mafic minerals range from entirely hornblende to entirely biotite. Minor phases include sphene, apatite, magnetite, ilmenite and pyrite.

There are two textural types of plagioclase: 1) Relict
Table 2. Modal analyses for quartz diorite unit.

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* Sample from compositional layering

1 Sample from late shear zone
subhedral and euhedral laths and 2) fine-grained, recrystallized granular plagioclase.

Reclit subhedral laths of plagioclase reach 2 to 3 mm in size and show a good foliation in most places (Figure 13). Plagioclase boundaries are embayed by quartz. Normal zoning is common and the cores of zoned grains are usually altered to saussurite. Composition of the plagioclase, determined by the Michel-Levy method ranges from An$_{38}$ to An$_{45}$ (andesine). The largest grains are slightly deformed or may be rimmed by small recrystallized grains.

Recrystallized plagioclase grains are less than 0.3 mm in size and often form granoblastic aggregates a few centimeters wide along foliation planes in the rock. Twinning in recrystallized plagioclase grains is rare.

Hornblende is subhedral and anhedral, and ranges in size from 0.4 to 2 mm. It is pleochroic with a straw yellow, green and blue green. 2V is about 70° and γ, λc is 16° - 18°. Twinning is common. Individual hornblende grains are subpoikiloblastic prisms with ragged edges.

Brown biotite forms subhedral and anhedral flakes intergrown with hornblende or as individual grains. Biotite is usually foliated. It is commonly altered to chlorite with anomalous purple interference colors.

Quartz is anhedral and ranges from 0.3 to 1 mm in size. It forms the matrix for euhedral plagioclase grains. It is commonly undulose and may have deformation bands parallel to the c axis.
Figure 13. Foliated plagioclase in quartz diorite at Holcombe Dam. Field of view is 6 mm. Sample number GN1.

Epidote forms euhedral prisms reaching 0.8 mm in size. It is colorless in thin section and occurs in association with hornblende and biotite or as an alteration of plagioclase, or sometimes in veins. Epidote grains cut across hornblende and biotite boundaries, and it probably was a late crystallizing phase.

Sphene, often with cores of ilmenite, is associated with biotite and chlorite. Sphene grains with one overgrowth have been observed.

Granite
The quartz diorite is intruded by granite which takes the forms of coarser grained pods with migmatitic contacts
and of finer grained dikes with sharp contacts (Figure 42). The granite is a pink, medium-grained, faintly foliated rock with a pink to rusty weathering surface. Portions of the granite intrusives have porphyritic microcline grains reaching 1 cm in size. The granite dikes are fine-grained with small pods of pegmatite.

Granitic intrusives have been named according to the classification of Streckeisen (1973) and would be called quartz monzonite by most other classifications. Granite intrusives consist of subequal amounts each of plagioclase, microcline and quartz, with minor amounts of biotite, muscovite and epidote. See Table 3 for modal analyses. Textures are hypidiomorphic and inequigranular (Figure 15).

Microcline forms large subhedral grains as well as smaller (0.3 to 5 mm) subhedral and anhedral grains in the surrounding rock. The large microcline grains sometimes contain inclusions of plagioclase, microcline and quartz, and usually display deformed twins and microfaulting. Smaller microcline grains have deformation lamellae. Small (0.3 mm) recrystallized grains occur along cracks and around the edges of the deformed microcline.

Subhedral and anhedral plagioclase ranges from 0.3 to 5 mm. Many grains are embayed by quartz or are partially recrystallized to a fine-grained aggregate. Plagioclase is also deformed, and twinning is usually too bent or faded to allow determination of the composition.

Myrmekite occasionally occurs on the edges of microcline
Figure 14. Migmatitic contact between granite and quartz diorite.

Figure 15. Hypidiomorphic, inequigranular texture in granite intrusive at Holcombe Dam. Field of view is 6 mm. Sample number GN622.
Table 3. Modal analyses from granitic rocks at Holcombe Dam.

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* Dike samples
grains, and more rarely on plagioclase.

Aggregates of fine-grained recrystallized feldspar often form stringers or trains parallel to the dominant foliation. Feldspar is extensively altered to sericite or saussurite, and is often stained pink by hematite.

Quartz is anhedral, 0.3 to 1.5 mm, and forms the matrix for the feldspars, similar to textures in the quartz diorite.

Biotite and muscovite occur intergrown in clots to 3 mm in size, or as individual grains to 1.5 mm. Muscovite also occurs as an alteration product of microcline. Both micas are usually slightly foliated.

Allanite forms euhedral grains up to 2.5 mm in size and is usually metamict. Sphene, often with ilmenite cores, is mostly associated with biotite.

Textures in the granite dikes are similar to those in the granite except that the rock is finer grained, with the largest feldspar less than 1.5 mm. See Figure 16. The dikes have fewer mafic minerals than associated intrusives and these are mostly concentrated at the dike contacts.

**Meta-andesite**

The youngest intrusive unit at Holcombe Dam, a hypabyssal andesite, intrudes the quartz diorite and granite dikes with sharp, steeply dipping contacts (Figure 17). It consists of about 10% lineated hornblende grains in a fine-grained pale gray matrix. Where the andesite crosscuts the granite dikes, it contains numerous pale green veins of epidote.

Hornblende porphyroblasts are long, narrow laths up to
Figure 16. Granite dike at Holcombe Dam shows textures similar to those in associated granite intrusives. Field of view is 6 mm. Sample GN641A.

Figure 17. Hammer lies along contact between fine-grained meta-andesite and medium-grained quartz diorite.
4 mm in length. See Figure 18. These usually contain inclusions of quartz and plagioclase. A few are bent or cracked and show undulatory extinction. The optical properties of hornblende are similar to those of hornblende in the quartz diorite gneiss. Hornblende grains sometimes contain abundant ilmenite needles concentrated at the cores.

The matrix is a fine-grained granular aggregate of plagioclase (45-55%) and quartz (12-15%), biotite (12-14%) and fine-grained anhedral hornblende (0-6%). A few euhedral laths of relict plagioclase to 1.5 mm remain, and these are usually bent and deformed. Biotite in the matrix is foliated.

Figure 18. Lineated laths of hornblende in a fine-grained matrix of plagioclase and quartz, from meta-andesite intrusive at Holcombe Dam. Field of view is 6 mm. Sample number GN638.
Hydrothermal Alteration

Late hydrothermal alteration occurred as the result of migrating solutions along fracture systems. Altered zones occur for a few centimeters on either side of these fractures. In these zones, plagioclase is completely altered to sericite or saussurite, and biotite has been converted to chlorite. Quartz is partially replaced by albite and/or calcite. Hornblende has developed overgrowths of pale actinolite. Chlorite and calcite also replace plagioclase in a few places.

This type of hydrothermal alteration is consistent with that produced by hydrogen metasomatism, along with the introduction of Na₂O and CO₂ (Meyer and Hemley, 1967).

Shear Zones

Shear zones crosscutting the quartz diorite gneiss are long, narrow, sinuous zones of schist, containing pods of quartz and pyrite or of quartz and feldspar. The shear zones range in width from a few millimeters to 1.5 meters and in length from a few centimeters to 60 meters. Shear zones can be observed crosscutting the quartz diorite gneiss and the andesite units. Although none have been observed crosscutting granite, they must be younger than the granite, since the andesite is the youngest rock unit present.

The rocks in the shear zones are thoroughly recrystallized schists which display no cataclastic textures. The schists are composed of 45-65% mafic minerals, which consist of every combination of chlorite, biotite and/or hornblende, as well as granular recrystallized plagioclase (20-40%) and lesser amounts
of quartz and epidote.

The conversion of quartz diorite to schist can be observed in thin sections cut across a small shear zone. Progressing from the edge of the shear zone inward, grain size decreases rapidly from 0.5 mm to an average of 0.1 mm as plagioclase from the quartz diorite recrystallizes into fine-grained aggregates. Mafic minerals also become fine-grained and wrap around remnant plagioclase grains as well as recrystallized plagioclase aggregates. Notably, epidote does not decrease in grain size but forms euhedral grains to 1 mm, or segregates into recrystallized granular aggregates. Toward the center of the shear zone, recrystallization has occurred, and a medium-grained laminated schist has formed in which zones with up to 90% mafic minerals alternate with layers of plagioclase and quartz on the scale of a few grain widths.

Within some of the larger shear zones, coarse-grained (3 mm to 1 cm) pods and veins up to 3 cm wide, of feldspar, quartz and small amounts of hornblende have been produced. Large hornblende grains can be observed nucleating on the edges of the quartz-feldspar veins. It may also occur within the veins as clots, or as fine needles in quartz veins. A few of these pods and veins contain microcline as the dominant feldspar. These veins are apparently the products of reactions involving biotite-plagioclase bearing assemblages. The reactions involved are similar to those hypothesized by Korzhinski (1959) for high temperature metamorphism of granitic rocks, and involve changes in $\mu K_2O$ and $\mu Na_2O$ in the rock.
Most of the feldspar formed in veins is plagioclase. These veins may be the result of reactions among biotite, epidote and pyrite.

Quartz usually composes more than half of the veins produced, and probably is remobilized from the quartz diorite.

**Interpretation**

The three intrusive rock units at Holcombe Dam all contain relict igneous subhedral and euhedral feldspars, and all have metamorphically induced fabrics, imparted dominantly by the mafic minerals. The quartz diorite also contains a faint compositional layering. These features suggest that all the intrusive units are synkinematic to late synkinematic.

Textural relationships in thin section suggest that a similar paragenesis applies to all three major intrusive rock units. The following sequence of crystallization can be inferred: plagioclase, (microcline), quartz, hornblende, biotite (ilmenite and sphene), epidote, chlorite, pyrite. The association of sphene with biotite in the quartz diorite and granite units is probably the result of the removal of titanium during metamorphic recrystallization of primary igneous biotite.

Schists in the shear zones are the result of concurrent shear deformation and recrystallization of quartz diorite. The sheared rock bears little resemblance to the original quartz diorite.
Amphibolite Schist along the Chippewa River

Amphibolite schist, exposed along the Chippewa River is thought to represent a major shear zone on the basis of its structural similarity to shear zones crosscutting the quartz diorite (see Structure, p. 72). Portions of the amphibolite schist contain large lenses of gneissic granite as well as slivers of granite along foliation planes. It also contains spotted mafic inclusions with white plagioclase rinds exactly like those found in the quartz diorite gneiss (Figure 44).

The amphibolite schist is a compositionally layered rock which shows numerous textural variations. The unit can be divided into three dominant textural types: coarsely banded varieties, finely banded rock, and portions which have no obvious compositional layering. Coarse banding takes the form of pods, lenticular bands and layers 2 to 7 cm wide of white plagioclase and quartz, alternating with fine-grained hornblende-plagioclase rich layers. See Figure 19. Fine banding is similar, but occurs on a scale of less than 2 millimeters. Unlayered portions of the rock may be composed of hornblende schist or of amphibolite schist, plagioclase-biotite schist or of plagioclase granofels.

Amphibolite schist, with or without banding, comprises the dominant part of the unit. It consists of 16-65% hornblende, 22-62% plagioclase and lesser amounts of quartz, epidote and biotite (see Table 4).

Hornblende usually forms subhedral prisms less than 1 mm in size, which display both a strong lineation and a strong
foliation (Figure 20). Optical properties are similar to those of hornblende in the quartz diorite unit.

Plagioclase forms fine-grained aggregates of untwinned grains. Grains may be tabular or granular. In zones where hornblende is less abundant, granular plagioclase shows good triple points. Plagioclase composition measured by the Michel-Levy method is An_{45} - An_{50}. This is a minimum estimate, since twinned grains are rare.

Scattered throughout the amphibolite schist and in felsic bands are numerous relict porphyroclasts of subhedral to lenticular plagioclase grains. These sometimes have quartz trains and foliation in the surrounding rock wraps around them (Figure 21). These porphyroclasts often display bent twinning
Table 4. Modal analyses from the amphibolite schist unit.

<table>
<thead>
<tr>
<th></th>
<th>MY13</th>
<th>MY22</th>
<th>MY32</th>
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<th>MY12</th>
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</table>

MY44, MY12A, MY13A and MY41 are felsic bands in the amphibolite schist.
Figure 20. Fine-grained amphibolite schist. Section cut parallel to lineation. Field of view is 6 mm. Sample number MY5-L.

Figure 21. Schistose hornblende wraps around plagioclase porphyroclast in amphibolite schist. Field of view is 6 mm. Sample number MY2.
and are polygonized.

Brown biotite is a minor constituent of the amphibolite schist. It is fine-grained and is nearly always foliated.

All the felsic bands in the rock are composed predominantly of plagioclase and quartz with minor hornblende and chlorite or biotite. In a few bands the dominant feldspar is orthoclase, but plagioclase is more common. Feldspar forms granular aggregates or sometimes tabular aggregates which alternate with quartz on the scale of a few millimeters. Coarser grained relict feldspars are also common.

Quartz throughout the unit is fine-grained to medium-grained and forms trains or pods parallel to foliation.

Epidote in the amphibolite schist is subhedral to anhedral and is often foliated. Opaques include pyrite, magnetite and ilmenite, all of which may be foliated. Sphene (usually associated with chlorite) and apatite are accessories.

Pods of gneissic granite in the amphibolite schist contain the same mineral assemblages as the granite at Holcombe Dam. All the feldspar is recrystallized into fine-grained granular aggregates which form pods and trains parallel to the dominant foliation. These are interlayered with recrystallized quartz. The feldspars are altered and are stained pink like those from the granite at Holcombe Dam.

**Hydrothermal Alteration** Hydrothermal alteration is similar to that in the quartz diorite, but the amphibolite schist has been altered more extensively than the quartz diorite. Most of the alteration occurs along fractures.
Plagioclase is converted to sericite or is albitized, hornblende alters to actinolite and/or chlorite and biotite alters to chlorite. Calcite replaces quartz, especially in felsic bands. Most of the epidote in the amphibolite schist is a late alteration product of plagioclase or of hornblende.

**Discussion and Interpretation**

Structural evidence indicates that the amphibolite schist was formed in a major shear zone. Pods of gneissic granite, and spotted mafic inclusions with white rims similar to those in the quartz diorite gneiss occur in the amphibolite schist suggesting that the amphibolite schist may have formed by the shearing and metamorphism of quartz diorite. In order to determine whether this is indeed the case, the average compositions of the two units was compared.

The average composition of the amphibolite schist was determined by direct measurement across the photograph in Figure 19. The average compositions of mafic and of felsic bands was calculated from the modal analyses in Table 4, and these were multiplied by the volume percent of each. The results were added together to determine the average composition of the amphibolite schist unit. The average composition of the quartz diorite was determined by averaging the modal compositions of quartz diorite samples in Table 2. The results of these calculations is shown in Table 5. The average composition of the andesite intrusive at Holcombe Dam was also included in Table 5 for comparison.

The average composition of the amphibolite schist as
determined above is dioritic in general, but is less siliceous and less potassic than the average quartz diorite gneiss. The estimated overall composition of the amphibolite schist is similar to some phases of the quartz diorite unit (see Table 2, sections 625, 635 and 656).

Table 5. Average modal compositions of quartz diorite, amphibolite schist and andesite from Holcombe, Wisc.

<table>
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<th>Quartz Diorite</th>
<th>Amphibolite Schist</th>
<th>Andesite</th>
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<td>Opaques</td>
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MESOSCOPIC STRUCTURE

Introduction

Structural features of rocks in the Holcombe area are complex and indicate several periods of deformation. Because the three major lithologic units examined exhibit different structural styles, their structural elements will be discussed separately. Then the entire area will be discussed in terms of an evolutionary model for sequential structural deformation.

Banded Gneiss at the Fisher River

The following structural interpretation is based on two major outcrops along the Fisher River. The other outcrops in the area are very small and did not render much useful information.

Penetrative Structures

Foliation

Three types of foliation can be recognized in rocks along the Fisher River: 1) preferred mineral orientation in amphibolite zones, 2) preferred mineral orientation in tonalite bands, and 3) lithologic layering of amphibolite with bands of tonalite. These three types of foliation are coplanar throughout most of the outcrop area. In a few places, the foliation in zones of amphibolite shows an anomalous discordance which will be discussed later.

Mineral foliation in amphibolite zones is caused primarily by the orientation of hornblende grains and clots, and of biotite grains. Rarely, lensoid xenoblastic grains of
quartz and plagioclase are aligned along foliation planes. Mafic inclusions in the amphibolite show a similar mineral foliation.

Bands of coarse-grained tonalite contain a strong mineral foliation defined by the alignment of biotite clots and chlorite grains. This mineral foliation parallels that in the surrounding amphibolite even where contacts of the banded tonalite crosscut foliation in the amphibolite.

A third type of foliation is defined by a lithologic banding of tonalite with amphibolite (Figure 3). Bands of tonalite are 1 cm to 15 cm wide. The width of a single band is not consistent across the outcrop, and individual bands often cannot be traced across the outcrop due to attenuation. This banding is at least partially a transposed foliation, produced during the isoclinal folding and shearing of original $S_0$ surfaces in the tonalite along an axis parallel to $S_1$ (Turner and Weiss, 1963). Translation of layers along $S_1$ has attenuated isoclinal fold limbs. Fold hinges are strongly appressed and locally have become separated from the limbs (Figure 22).

The dominant foliation in the banded gneiss unit generally strikes east-west, but may vary in attitude from N70E to N70W with near vertical dips (see Figure 23). The fairly wide variation in strike is the result of a broad warping of foliation which occurred during a later fold deformation. Foliation in the amphibolite is axial planar to minor $F_1$ folds developed in the tonalite.
Strain analysis was undertaken on one sample of coarse-grained tonalite. At least 50 biotite clots were measured from each of three orthogonal faces cut parallel and perpendicular to foliation. The data was reduced using a PASE program of Dunnett and Siddans. Results indicate that the tonalite is characterized by a flattened fabric ($v = 1.5, k_f = 0.62$) with relatively high strain values ($\epsilon = 1.6$) for this type of assemblage (Davidson, 1977).

Lineation

Three types of lineations were observed in rocks at the Fisher River: mineral lineations, fold axes, and boudinage. All lineations occur within the plane of foliation.
Figure 23. Equal area plot of poles to foliation planes from the banded gneiss unit along the Fisher River. 44 total data points.
Mineral lineations in rocks at the Fisher River occur in zones of amphibolite. These lineations are the result of a crude orientation of hornblende crystals ranging from 1-2 mm in size. A similar lineation also occurs in mafic dikes in the amphibolite. Mineral lineation due to biotite streaking in bands of tonalite was only observed in one place, where it plunged in a direction parallel to that of the mineral lineation in the surrounding amphibolite.

Nearly all fold axes were measured from minor folds in small veins of tonalite. Fifteen minor fold axes were measured in all.

Boudinage is not common in outcrops along the Fisher River, but can be found occasionally along the limbs of larger folds (Figure 24). They are always elongate in the plane of foliation. Lineations associated with boudinage were parallel to mineral lineations in surrounding amphibolite.

Except for mineral lineations associated with an anomalous fold set in the amphibolite (discussed later), all the lineations display a regular distribution on the outcrop. Along a north-south traverse across foliation, lineations become steep to vertical and then begin to plunge shallowly to the west. All the lineations within a given foliation plane have a similar orientation (Figure 25).

Fold axes and mineral lineations define a steeply dipping great circle when plotted on a stereonet (Figures 26 and 27). When superimposed, both mineral lineations and fold axis lineations define the same great circle. This implies that
Figure 24. Boudinage and pinch and swell in tonalite vein along the limb of a folded mafic dike. The fold hinge is off the right hand side of the photograph.

Figure 25. Diagrammatic distribution of lineations in the plane of foliation along a north-south traverse across foliation.
Figure 26. Equal area plot of minor fold axes in the banded gneiss unit at the Fisher River. 15 measurements.
Figure 27. Equal area plot of mineral lineations in banded gneiss at the Fisher River. Circles represent lineations measured in anomalous fold hinge at the north end of the outcrop area. Crosses represent the same for the anomalous fold at the south end of the outcrop, 14 measurements total.
secondary folding occurred in a rock that was previously folded, lineated and metamorphosed. The second deformation passively folded previous lineations. Lineations which show a great circle distribution due to refolding may be produced during refolding by simple shear (Ramsay, 1967).

Folds

The banded gneiss at the Fisher River has been affected by at least three periods of folding, designated $F_1$, $F_2$, and $F_3$. Evidence for all three periods of folding can be observed on the limited outcrop available.

$F_1$ folding formed isoclinal folds in tonalite banding as well as minor folds in small veins of tonalite. During $F_1$, two distinct domains with different styles of folding and deformation were formed (see Figure 28). In areas designated as Domain I in Figure 28, foliated tonalite banding formed in discrete areas 3 to 4 meters wide, probably in response to isoclinal folding and shearing of original $S_0$ surfaces. In the intervening areas, designated as Domain II on Figure 28, small folds with wavelengths of only a few centimeters were produced in thin veinlets of tonalite which crosscut foliation in the host amphibolite. Veinlets perpendicular, or at a high angle to foliation form folds to which foliation in the amphibolite is axial planar. Where veins occur parallel to, or at a low angle to foliation, they are unfolded, or more rarely, exhibit extensional features such as boudinage. Many of the minor folds in Domain II are ptygmatic in form. Minor folds also occur in apophyses of the larger tonalite banding. A few
Figure 28. Outcrop map from the Fisher River showing lineations and extent of structural domains. Domain I shows zones in which tonalite banding occurs. Domain II indicates zones in which the rock type is dominantly amphibolite with small folded veins of tonalite.
tonalite veins contain S or Z folds. These have no apparent significant distribution.

The axial planes of all \( F_1 \) folds strike in the same direction as foliation, or generally east-west. Plunges of axes from minor folds in Domain II were discussed previously.

Since the morphology of folds from Domain II is variable, an attempt to characterize the various fold styles has been made. Three minor folds were described and classified by analyzing their geometry according to the methods of Ramsay (1967) and Hudleston (1973). Somewhat idealized forms were used in order to avoid difficulties created by minor irregularities in the fold form.

Where folds could be observed in profile (perpendicular to the axial plane), Ramsay's method was utilized. Dip isogons were drawn on the fold profile and the thickness of the layer, \( t_\alpha \), was measured normal to the tangents of the bounding surfaces at an angle \( \alpha \) from the axial trace of the fold. Then the value \( t'_\alpha = t_\alpha / t_0 \) was plotted against the value of \( \alpha \), where \( t_0 \) is the thickness at the fold hinge. The class of the fold under consideration was then determined.

Where folds could not be observed in profile, a modification of Ramsay's method proposed by Hudleston (1973) was used. In this method, a parameter, \( \Theta_\alpha \) is defined as the angle normal to the tangents to the fold surfaces and the isogon for a given \( \alpha \).

Figure 29 shows a Z fold formed in a thin band of tonalite. It was analysed using the method of Hudleston (1973). The
isogon plot shows it to be a class 1C fold.

Figure 30 shows a typical ptygmatic fold in outcrop. It consists of a series of small folds within a larger, folded vein of tonalite. The two synforms analyzed are class 1C folds, but they plot very close to class 2.

The minor fold shown in Figure 31 shows a combination of fold forms. The synform on the right has the isogon pattern of a class 3 fold and the adjacent antiform and synform are class 1C folds.

The differences in fold forms within Domain II at the Fisher River appears most directly related to the heterogeneous nature of the rock. The resulting variation in rheologic properties of the compositional layering cause a considerable variation in the state of strain over the outcrop during deformation.

The previous discussion applies to $F_1$ folds in tonalite bands and veinlets. $F_1$ folds in the amphibolite unit are not common. Two small isoclinal folds were observed in the primary compositional layering, but because there was no relief on the outcrop, plunges could not be measured. The axial traces of these folds trend in the same direction as the surrounding foliation. A mesoscopic isoclinal fold with a wavelength of 1 meter occurs in a spotted mafic dike in the amphibolite. It is pictured in Figure 24. The fold axis is nearly vertical, with an axial plane which lies in the plane of foliation.

$F_2$ folds can be recognized at one place near the south
Figure 29a. Z fold in tonalite vein.

Figure 29b. Isogon plot.

Figure 29c. Plot of $\theta$ vs. $\alpha$. 
Figure 30a. Ptygmatic fold in tonalite vein.

Figure 30b. Isogon patterns for two synforms.

Figure 30c. Plot of $\theta_\alpha$ vs. $\alpha$. 
Figure 31a. Minor fold in tonalite vein.

Figure 31b. Isogon pattern.

Figure 31c. Plot of $t_a$ vs. $\alpha$. 
end of the outcrop area where both tonalite banding and foliation in the host amphibolite have been folded into tight, accordion style folds. These folds trend N60W to N85E and plunge 60° to 79° in a northwesterly direction. Wavelengths reach 1.5 meters. The wide variation in the trend of the folds is probably due to reorientation during a later, F3 fold event. The presence of F2 folds too large to be observed on the rest of the available outcrop is evident from the distribution of L1 lineations described earlier.

The nature of the F2 folding event can best be described by a model proposed by Ramsay (1967, p. 474) for the deformation of linear structures (see Figure 32). In this model,

Figure 32. Pattern of deformed lineations on surfaces r,s,t,u resulting when the shear plane ab intersects the surfaces at an oblique angle. This model accurately describes the distribution of lineations observed in the banded gneiss at the Fisher River. (After Ramsay, 1967, Figure 8-13.)
a set of original plane surfaces \((r,s,t,u)\) in Figure 32) containing a lineation is folded in such a way that the dihedral angle between the \(ab\) plane (the plane of flow) and the original surfaces is small. The movement direction, \(a\), is contained in the original surfaces. The effect is to produce abrupt changes in the plunges of lineations on the outcrop. Ramsay's model describes the \(F_2\) deformation of rocks at the Fisher River if one imagines the \(a\) (movement) direction to be near horizontal rather than vertical as it is in Figure 32.

The \(F_3\) fold deformation produced broad, open folds which affect all the foliation as well as \(F_1\) and \(F_2\) fold axes in the banded gneiss. Tonalite banding and foliation in the amphibolite have been broadly warped along a north-south axis which plunges almost vertically. The contacts of some of the tonalite bands were traced out on the outcrop map in Figure 28 in order to delineate the nature of \(F_3\) folding. The folds are disharmonic features with wavelengths of 6 to 10 meters.

Two mesoscopic folds in the amphibolite unit display anomalous structural characteristics compared to \(F_1\), \(F_2\) and \(F_3\) folds. They occur as flexures in foliation between bands of tonalite. Where these folds occur, foliation strikes at a high angle to the surrounding foliation and is truncated on either side by bands of tonalite (see Figure 33). One of these folds, located at the south end of the outcrop area plunges \(30^\circ W\) and the other, at the north end of the outcrop
area plunges vertically. The axial planes of both of these folds are parallel to foliation in the surrounding banded gneiss. Mineral lineations associated with the two folds plunge shallowly at 8° N and trend around the fold hinge (see Figure 27).

The occurrence of these two anomalous folds cannot be logically explained by any of the three folding events which affected the rest of the banded gneiss, and the cause of their formation is uncertain. It is likely that either these folds are remnants of an early phase of deformation.
which for unknown reasons is only preserved at those two places, or they formed during late translation along or adjacent to the bands of tonalite.

**Non-Penetrative Structures**

No shear zones were observed in the outcrops exposed along the Fisher River. The banded gneiss is crosscut by a few faults and a number of joints, most of which have been healed by epidote, chlorite or quartz. The trend of these fractures is the same as those of fractures in the gneiss at Holcombe Dam, and will be discussed below.

**Quartz Diorite Gneiss and Intrusives at Holcombe Dam**

**Penetrative Structures**

The quartz diorite gneiss unit at Holcombe Dam contains a penetrative foliation, \( S_1 \), parallel to \( S_1 \) in the amphibolite at the Fisher River. Foliation is defined by the orientation of hornblende, biotite and of plagioclase. Mineral foliation in the gneiss parallels the compositional layering, even where it is folded. Compositional layering is faint, and consists of discontinuous lenses and layers more rich in plagioclase and quartz. The attitude of the foliation surface was only measured where compositional layering was present as it was difficult to directly measure it elsewhere. The foliation strikes dominantly east-west and dips vertically (Figure 34).

No lineations were observed in the quartz diorite gneiss. Mineral lineations apparently do not exist on a mesoscopic scale. No fold axes could be observed.

Both ultramafic and mafic inclusions are foliated.
Figure 34. Equal area plot of poles to foliation from quartz diorite gneiss at Holcombe Dam. Contours at 25, 20, 10, and 1 percent per one percent area. 99 data points were plotted.
Schistosity in the ultramafic inclusions parallels foliation in the gneiss unit. Foliation in the spotted mafic inclusions, due to the orientation of large hornblende clots, usually occurs only at the margins and is parallel to the contact of the inclusion with the gneiss. Foliation in the quartz diorite gneiss wraps around the inclusions. This relationship holds even when the inclusions lie discordant to the dominant foliation.

The small granite intrusions which cut the host gneiss contain a faint foliation and lineation due to the orientation of biotite grains and clots. Foliation and lineation were difficult to ascertain in the field owing to poor exposure. Three measurements of foliation from oriented samples gave readings of N60E to N90E. Dips are almost vertical. No lineation could be observed in hand samples of granite which were collected, however, it could be observed in the field: there it plunges moderately to steeply (60-80°) to the west within the plane of foliation.

Three parallel granite dikes associated with the above mentioned intrusives have an average strike of N60E and dip 70° NW except where disrupted by faulting. Foliation in the surrounding gneiss is sheared in places along the dike contacts. Foliation in the quartz diorite gneiss along the contact with these dikes is occasionally bent in such a way as to indicate left-lateral movement.

The meta-andesite intrusive associated with the gneiss in this area contains a very faint foliation and a strongly
developed hornblende lineation. Foliation trends from N52E to 
N85E. Lineations plunge 37° to 85° SW (Figure 35). These 
structural trends are similar to the trends observed in $F_2$
foliations in the area, and to trends in shear zones and in the 
amphibolite schist. The andesite contains enclaves of quartz 
diorite gneiss up to 7 meters in length. The long axes of 
these enclaves parallel the contact between the andesite 
unit and the quartz diorite. Foliation in the rafts does 
not differ from that in the host gneiss, indicating little or no rotation of the blocks has taken place.

Folds in the rocks at Holcombe Dam occur only in the 
host quartz diorite gneiss. Most of these are small with 
wave-lengths of a few centimeters, and involve the composi-
tional layering, although a few folds do occur in felsic 
veins. Not a single fold axis was exposed, so only the 
traces of axial planes were measured. Trends of the axial 
planes range from N45E to east-west. $S_1$ foliation was observed 
to be folded along with the compositional layering, indicating 
that folds in the quartz diorite are $F_2$ folds.

Two folds from the quartz diorite gneiss have been 
classified according to the method of Hudleston (1973).

Figure 36 shows a small isoclinal fold in the composi-
tional layering which displays a complex fold form. Of the 
two fold forms, the right limbs both plot as class 3 folds, 
and left limbs plot as class 1C folds.

Figure 37 is a fold in a small felsic vein. Isogon 
patterns indicate that it is a class 1C fold.
Figure 35. Equal area plot of lineations in the hypabyssal andesite intrusive at Holcombe Dam.
Figure 36a. Isoclinal fold in compositional layering in quartz diorite gneiss.

Figure 36b. Isogon pattern.

Figure 36c. Plot of $\theta_a$ vs. $a$. 
Figure 37a. Fold in felsic vein in quartz diorite gneiss.

Figure 37b. Isogon pattern.

Figure 37c. Plot of $Q_a$ vs. $a$. 
Non-Penetrative Structures

Shear Zones

Shear zones which crosscut the quartz diorite gneiss and the andesite units are regularly spaced and discontinuous. The boundaries of the shear zones with the gneiss are usually sharp, and reorientation of gneissic foliation is abrupt. Rarely, foliation of the gneiss along the shear zone boundaries has been bent in such a way as to indicate left-lateral displacement (Figure 38). Ultramafic inclusions caught up in the shear zones are flattened in the plane of schistosity.

Schistosity in the shear zones has an average strike of N65E and dips vertically to steeply north, although it can be observed dipping moderately to the south (see Figure 39).

Figure 38. Small shear zone in quartz diorite gneiss.
Figure 39. Poles to schistosity in shear zones crosscutting quartz diorite gneiss and intrusives at Holcombe Dam.
Schistosity generally parallels the boundaries of the shear zones. Lineations were observed in three places within the plane of schistosity. These plunged moderately (40°) to the west. The trends of both schistosity and lineations in the shear zones parallels that of the amphibolite schist which is exposed farther down the Chippewa River, suggesting that the two are related.

A cataclastic shear zone at least 8 meters wide is exposed at the northwest corner of the outcrop area. The gneiss in this shear zone is schistose and shows cataclastic textures in thin section. Granite dikes and the meta-andesite are also schistose in the shear zone. Large, unsheared lenses in the shear zone give the appearance of having undergone spheroidal weathering (Figure 40). Structural trends in this shear zone are similar to those of other shear zones in the quartz diorite gneiss. The cataclastic nature of the shear zone suggests that it is a late phenomenon.

Fractures

Fractures measured at Holcombe Dam and along the Fisher River are similar in orientation and thus will be discussed together. Unlike fractures at the Fisher River, almost none of the fractures at Holcombe Dam are filled with secondary minerals. All the fractures in the area dip steeply to vertically.

Fractures measured from rocks at the Fisher River and at Holcombe Dam are plotted in Figure 41. Of these, the sets trending dominantly N50W and N20W are faults. All the
Figure 40. Unsheared lense of quartz diorite in shear zone gives the impression that spheroidal weathering has occurred.

Figure 41. Azimuths of fractures at the Fisher River and at Holcombe Dam. Scale in data points, 110 data points total.
others are joints.

The fault set trending N50W is best developed at Holcombe Dam. Here, granite dikes have been slivered and displaced by strike-slip movement along them (Figure 42). Both right and left lateral offset can be observed along the faults. A plot of the amount of offset on the faults versus the sense of displacement along one dike reveals that right-lateral faults are dominant, and have the largest amount of offset (see Figure 43). The fault set trending N20W and the N50W set probably formed contemporaneously, since the two can be found offsetting each other.

Figure 42. Granite dike offset by both right and left lateral faults which trend N50W. Located at Holcombe Dam.
Figure 43. Plot of offset on faults vs. their strike.

R = right lateral offset
L = left lateral offset

The right lateral faults are clearly dominant and have the largest amount of offset.
A joint set trends N55E and dips nearly vertically. Another set, trending north-south can be found crosscutting the two major fault sets.

**Amphibolite Schist Along the Chippewa River**

Since the amphibolite schist displays all the same structural characteristics as the smaller shear zones in the quartz diorite gneiss, it is interpreted to represent a major shear zone which crosscuts the area of study. The exposed shear zone strikes N70E and is at least 800 meters wide. The proximity and orientation of the shear zone to the proposed location of the Jump River Fault, as envisioned by Sims, Cannon and Mudrey (1978) suggests that they may be associated structures.

**Penetrative Structures**

Foliation in the amphibolite schist is very well developed and a cleavage has been produced parallel to it. Schistosity is defined by the orientation of hornblende and biotite. As mentioned previously, the amphibolite schist is a banded rock in most places. Plagioclase-quartz rich bands weather as ridges on the outcrop. Schistosity, cleavage and compositional layering are parallel throughout the unit.

In one place, a spotted mafic inclusion similar to those found in the quartz diorite gneiss unit at Holcombe Dam was observed. Here, it had been stretched along the plane of foliation in the schist (Figure 44). Mineral foliation within the inclusion paralleled that of the surrounding amphibolite
Figure 44. Spotted mafic inclusion similar to those in the gneiss at Holcombe Dam, is flattened along the plane of foliation in the amphibolite schist.

Schistosity and compositional layering have an average strike of N70E and dips are almost vertical. See Figure 45. A small variation in strike is due to the sinuosity of compositional layering.

Mineral lineations are extremely well developed in the amphibolite schist. They are the result of the alignment of hornblende laths within the plane of schistosity. Occasionally linear grains of pyrite also lie parallel to the lineations. Lineations have an average trend of N65E and plunge 42° SW (Figure 46). No eastward plunging lineations were observed.

Fold axes are also common in the amphibolite schist.
Figure 45. Poles to schistosity in amphibolite schist unit exposed along the Chippewa River. 35 data points.
Figure 46. Lineations in the amphibolite schist along the Chippewa River. Dots are mineral lineations. Circles are fold axes. 22 total data points.
These are everywhere parallel to mineral lineations. They are shown in Figure 46 also.

One structure, which might be interpreted as a boudinage structure, was observed in the amphibolite schist where a coarser grained layer of quartz diorite in the schist appears to be pulled apart within the foliation plane. The lineation associated with this structure was not measurable.

Intrafolial folds, which are commonly developed in the compositional layering are tight to isoclinal. Most of the folds in the amphibolite schist are single antiforms with no associated synforms. Intrafolial folds which plunge in the same direction as the dominant lineation are thought to be common features in blastomylonites (Higgins, 1971). All the folds are small, the largest measuring 6 cm across. Occasionally, a secondary axial planar foliation has developed.

Evidence of shearing was observed in one fold, where one limb has been disrupted by a shear plane passing through it (Figure 47).

Two folds from the amphibolite schist were classified according to the method of Hudleston (1973). Figure 48 shows a small intrafolial fold in a plagioclase rich layer. Its isogon pattern reveals it to belong to class 1C.

Figure 49 displays a multilayered fold. Individual layers show complex fold forms. The outermost two layers analyzed are class 1C and class 3 folds respectively. Alternating class 1C and class 3 folds are typical in multilayered folds. The innermost layer shows a complex fold form, where
Figure 47. Fold with sheared limb in amphibolite schist.
Figure 48a. Intrafolial fold in amphibolite schist.

Figure 48b. Isogon pattern.

Figure 48c. Plot of $\theta_a$ vs. $\alpha$. 
Figure 49a. Multilayered fold, amphibolite schist.

Figure 49b. Isogon pattern.

Figure 49c. Plot of $Q_a$ vs. $a$. 

Figure 49a. Multilayered fold, amphibolite schist.
the left limb plots as a class 1C fold and the right one as a class 1A fold.

The geometry of folds in the amphibolite schist indicates that they may have formed by buckling and flattening. Later shearing caused the folds to become isolated, rootless folds.

**Non-Penetrative Structures**

The amphibolite schist unit is crosscut by numerous fractures. These are especially evident in zones of amphibolite schist which lack compositional layering. Many of the fractures in the amphibolite schist are filled with secondary minerals such as epidote and chlorite. The azimuths of steeply dipping fractures are plotted in Figure 50. The two major fault sets developed in the rest of the area are also very well developed in the amphibolite schist, although there is a much greater scatter in the strike of these faults. This scatter may be due to difficulties in measurement, since many of the fractures were filled with secondary minerals, and their exact strike could only be determined within about 10°.

An additional fault set, apparently exclusive to the amphibolite schist trends N70E and dips vertically. Pods and linear zones of brecciated schist can be found along this set. See Figure 51. Occasionally, the N70E set offsets the N50E and N20E fault sets indicating it is the youngest set.
Figure 50. Azimuths of steeply dipping fractures in the amphibolite schist. Scale in number of points. 75 total data points.

Figure 51. Linear zone of breccia along foliation plane in amphibolite schist unit.
Summary and Conclusions

Structural analysis of the rocks at Holcombe, Wisconsin was undertaken in order to determine the phases of deformation and their evolutionary sequence. Although the outcrops are scattered and relations between the major rock types are not well exposed, a probable sequence of events can be determined from relationships exposed on the outcrops. This sequence of events is shown in Table 6. Several phases of deformation are evident, and it cannot be determined whether these are the result of a single deformational-metamorphic event, or whether several such events are represented.

The earliest phase of deformation produced the major structures in the area. A dominantly east-west, vertically dipping foliation, $S_1$, was produced in the banded gneiss and in the quartz diorite gneiss. Both mineral foliation and a compositional layering were produced in the rock units. In the banded gneiss, a lithologic layering of tonalite with amphibolite was produced, probably during the transposition of an original $S_0$ surface of the tonalite to $S_1$. In the quartz diorite gneiss, a faint metamorphically induced compositional layering formed parallel to mineral foliation. Mineral lineations were also formed in the amphibolite at the Fisher River.

During the first phase of deformation, isoclinal folds, $F_1$, were produced in the banded gneiss at the Fisher River. In the banded gneiss, two structural domains were produced during $F_1$ deformation. Attenuated isoclinal folds were
<table>
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<tr>
<th></th>
<th>Banded Gneiss- Fisher River</th>
<th>Quartz Diorite Gneiss-Holcombe Dam</th>
<th>Amphibolite schist-Chippewa River</th>
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</thead>
<tbody>
<tr>
<td><strong>D&lt;sub&gt;1&lt;/sub&gt;</strong></td>
<td><strong>F&lt;sub&gt;1&lt;/sub&gt;</strong> Isoclinal folds</td>
<td>Penetrative foliation and lithologic layering trending E-W</td>
<td>Penetrative foliation trending E-W</td>
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<td></td>
<td><strong>S&lt;sub&gt;1&lt;/sub&gt;</strong> Penetrative fold axis and mineral lineations</td>
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<td><strong>L&lt;sub&gt;1&lt;/sub&gt;</strong> Tight to isoclinal folds, folding <strong>F&lt;sub&gt;1&lt;/sub&gt;, S&lt;sub&gt;1&lt;/sub&gt; and L&lt;sub&gt;1&lt;/sub&gt;</strong></td>
<td>Tight to isoclinal folds folding <strong>S&lt;sub&gt;1&lt;/sub&gt;</strong></td>
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<td><strong>D&lt;sub&gt;2&lt;/sub&gt;</strong></td>
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<td>Penetrative lineations in granite and andesite</td>
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<td></td>
<td><strong>L&lt;sub&gt;2&lt;/sub&gt;</strong> Broad warping along N-S trend</td>
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<td><strong>D&lt;sub&gt;3&lt;/sub&gt;</strong></td>
<td><strong>F&lt;sub&gt;3&lt;/sub&gt;</strong></td>
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<td>Folding of <strong>S&lt;sub&gt;4&lt;/sub&gt;</strong> and shearing form rootless folds</td>
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<td><strong>D&lt;sub&gt;4&lt;/sub&gt;</strong></td>
<td><strong>S&lt;sub&gt;4&lt;/sub&gt;</strong> Faulting along discrete planes at N50W and N20W</td>
<td>Faulting along discrete planes at N50W and N20W</td>
<td>Faulting along discrete planes at N50W and N20W</td>
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<td>Late faulting along <strong>S&lt;sub&gt;4&lt;/sub&gt;</strong> planes at N70E</td>
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</table>
produced in the tonalite banding of Domain I. Continued translation produced rootless fold hinges in parts of the tonalite banding. In Domain II a variety of minor folds formed in small intrusive veins of tonalite. Foliation in the host amphibolite gneiss is axial planar to these minor folds. All $F_1$ folds trend east-west. The axes of $F_1$ folds formed parallel to mineral lineations.

$F_2$ folds occur in the banded gneiss unit and in the quartz diorite gneiss unit. In the banded gneiss, a series of tight accordion style $F_2$ folds were formed. A series of large scale $F_2$ folds reoriented $L_1$ lineations along a steeply dipping great circle. A model which describes the distribution of the folded lineations shows that $F_2$ folds trend at an oblique angle to $F_1$ folds, and plunge moderately to steeply.

$F_2$ folds in the quartz diorite gneiss are tight to isoclinal folds in $S_1$ foliation in felsic veins.

$F_3$ folding affected the banded gneiss, the quartz diorite gneiss and granitic intrusives. During $F_3$ folding, foliation and fold axial planes in both the gneisses were broadly warped along a steeply dipping north-south axis.

No $F_1$ or $F_2$ folds were observed in granite intrusives nor in the hypabyssal andesite intrusive at Holcombe Dam, although these rocks do contain a faint foliation similar in orientation to both $F_2$ fold axial trends, and the trends of the shear zones crosscutting the quartz diorite gneiss. The andesite is dominated by a strong linear fabric. The fabric of the
granite and andesite units cannot be directly related to the formation of shear zones, since the shear zones crosscut these units. It is probable that granite intrusives and meta-andesite are synkinematic intrusives formed during the $F_2$ fold deformation.

An extensive period of shearing affected the rocks in the Holcombe area. A series of small shear zones formed in the gneiss, coincident with the formation of the amphibolite schist. The amphibolite schist displays all the same structural characteristics as the smaller shear zones in the quartz diorite gneiss. For this reason, the amphibolite schist is interpreted to represent a major shear zone which crosscuts the area. There is local evidence of shearing and cataclasis within the amphibolite schist. The amphibolite schist displays some characteristics which are associated with blastomylonites (i.e. intrafolial folds), but the evidence for cataclasis is too local to justify classifying the rock as a blastomylonite.

A strong schistosity and a strong lineation developed in the amphibolite schist, as well as small folds in more competent layers in the schistosity. Continued shearing or translation along foliation planes caused these to separate, forming rootless folds.

A northeast trending shear zone at the northwest corner of the exposed quartz diorite converted the gneiss to mylonite schist and produced a schistosity in a granite dike and in andesite in the zone. It probably formed late during the
shearing event.

It is hypothesized that the Jump River Fault trends through the area of study (Sims, Cannon and Mudrey, 1978). It is apparent from observation of the aeromagnetic maps for the region that the trace of the fault was mapped along the edge of a linear negative anomaly which trends southwestward from the Jump River through the Holcombe area (see Figure 52). No outcrops occur at or near the suggested trace of the fault, so there is no direct evidence that it exists at that location. The fact that the shear zone in which the amphibolite schist formed trends in a direction similar to that of the aeromagnetic anomaly suggests that the shear zone itself is the cause of the anomaly, rather than a fault.

The final phases of deformation produced brittle faulting throughout the area. A set of faults trending N50W and N20W offset all the other structural features in the area. The N50W set is strongly developed and displays both right and left lateral strike separation, although right lateral offset is dominant.

A late period of faulting affected only the amphibolite schist unit. Fault movement along foliation planes offset other faults in the area, and brecciated the previously formed schist along foliation planes.

Although there are no age determinations for the area of study, the structural evidence, when compared with that for other areas in Wisconsin suggest that the deformation is Penokean in age. Maass (1977 studied the age of a similar
Figure 52. Aeromagnetic map of the area around Holcombe, Wisc. showing the trace of the Jump River Fault as proposed by Sims, Cannon and Mudrey (1978). Scale is 1/62500. Boxed in area includes sections 20, 21, 22, 27, 28, 29, 32, 33 and 34 in T32N, R6W. The trace of the town of Holcombe was included for reference.
deformational sequence between Stevens Point and Wisconsin Rapids, Wisconsin. U-Pb analysis of zircons from deformed tonalites in this area have yielded ages of 1850 m.y. to 1800 m.y. The zircon ages are interpreted to represent the times of emplacement of tonalite, and the age of the deformation is thus interpreted to be Penokean. (Maass et al., 1977). The phases of fold deformation in the Stevens Point area as reported, are almost the same in form, trend and relationships to each other as those at Holcombe, Wisconsin.

**SUMMARY AND CONCLUSIONS**

Table 7 contains a synthesis of all structural, igneous and metamorphic events affecting the rocks at Holcombe, Wisconsin. All of the rock units in the area have undergone partial to extensive recrystallization in the lower amphibolite facies. During the first phase of deformation, the volcanic breccia at the Fisher River was extensively deformed, folded and recrystallized in the amphibolite facies. Tonalite, which formed at the same time, was partially recrystallized and contains relict igneous feldspar. Quartz diorite was intruded and partially recrystallized during the first phase of deformation. Recrystallization continued after the F1 deformation, producing garnets in the amphibolite at the Fisher River.

The second deformational event refolded the banded gneiss and produced folds in quartz diorite. Granite and andesite intrusives in the quartz diorite have moderate to steep lineations which may have been produced during F2. Amphibolite facies metamorphism continued during the second phase of defor-
Table 7. Summary of structural, igneous and metamorphic events at Holcombe, Wisc.

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<thead>
<tr>
<th>Structural Event</th>
<th>Igneous Event</th>
<th>Metamorphic Event</th>
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<tr>
<td><strong>oldest</strong></td>
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<tr>
<td>$F_1, S_1, L_1$</td>
<td>Formation of amphibolite</td>
<td>Recrystallization in lower amphibolite facies</td>
</tr>
<tr>
<td></td>
<td>Formation of tonalite banding</td>
<td>Lower amphibolite facies recrystallization</td>
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<tr>
<td></td>
<td>Intrusion of quartz diorite</td>
<td>Garnets form in amphibolite</td>
</tr>
<tr>
<td>$F_2, L_2$</td>
<td>Intrusion of granite</td>
<td>Recrystallization in lower amphibolite facies</td>
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<tr>
<td>$F_3$</td>
<td>Intrusion of andesite</td>
<td></td>
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<tr>
<td>$S_4, F_4, L_4$</td>
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<tr>
<td>Various stages of faulting</td>
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**youngest**
mation, partially recrystallizing the granite and meta-andesite units.

The final fold deformation, F3, produced a broad warping of previously developed foliations and was apparently not accompanied by metamorphism.

During a fourth deformational event, shearing produced minor shear zones in the quartz diorite gneiss. Concurrent shearing and recrystallization (again in the amphibolite facies) produced the amphibolite schist from a protolith of andesitic composition.

Late shearing of the quartz diorite was accompanied only by weak recrystallization. Dominantly cataclastic textures were produced in the rock units in the late shear zone.

Late hydrothermal alteration affected the quartz diorite and the amphibolite schist, producing chlorite, actinolite, albite and calcite in the rocks.

All the rock units were affected by several late stages of faulting and jointing.

As stated in the Introduction, the Holcombe area lies at or near the boundary between the Chippewa Amphibolite Complex, consisting of amphibolitic gneisses and schists, and the Flambeau Volcani-sedimentary Province, consisting dominantly of intermediate to felsic volcanics. The amphibolite gneisses and schists, and the quartz diorite gneiss of the Holcombe area are interpreted to lie within the Chippewa Complex.

No direct evidence for the presence of the Jump River Fault exists in the Holcombe area, although the amphibolite
schist, interpreted to represent a major shear zone, occurs along the postulated trend of the fault. Since it crosscuts the area of study, it must lie within the Chippewa Amphibolite Complex, and cannot represent the boundary between the Chippewa Complex and the Flambeau Province, which must be further to the north.
REFERENCES CITED


