Structural Analysis of Archean Rocks in the Negaunee Area, Michigan—Constraints on Archean Versus Early Proterozoic Deformation

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Chapter O

Structural Analysis of Archean Rocks in the Negaunee Area, Michigan—Constraints on Archean Versus Early Proterozoic Deformation

By S.A. NACHATILO and R.L. BAUER

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P.K. SIMS and L.M.H. CARTER, Editors

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By S.A. Nachatilo[1] *and* R.L. Bauer[1]

Abstract

A detailed analysis of deformation features and finite strain in the Archean rocks of the Ishpeming greenstone belt near Negaunee, Michigan, was undertaken to evaluate the deformation history of the area and to determine whether the Archean rocks sustained significant ductile deformation during the Early Proterozoic Penokean orogenic event. Our study indicates that the Penokean orogeny was primarily a thin-skinned event in the Negaunee region and produced little ductile deformation in the Archean rocks.

Four periods of deformation, interpreted to be of Archean age, affected the Archean rocks. D_1 deformation is of local extent and is defined by a flat-lying foliation that is folded by F_2 crenulations. D_2 deformation significantly shortened the greenstone belt in a north to north-northeast direction and produced a nearly vertical west-northwest-striking S_2 foliation that is axial-planar to upright F_2 folds and crenulations. Finite strain analyses indicate constrictional D_2 strains with steeply plunging X axes. D_3 deformation produced brittle-ductile steeply dipping shear zones with north-side-up dip-slip movement that is consistent with a north-plunging maximum principal stress axis. D_4 deformation produced prominent crenulations, local kink bands with monoclinic symmetry, and steeply dipping strike-slip shear zones during a period of northwest-directed shortening.

The S_2 foliation in the Archean rocks and the orientation of the axial planes of Early Proterozoic folds are subparallel. However, D_3 and D_4 deformation features that deform the Archean rocks are not recognized in Early Proterozoic rocks and apparently developed during the Archean. Therefore, the D_2 structures in Archean rocks, which are parallel to regional Early Proterozoic structures, are Archean in age. We conclude that the Early Proterozoic Penokean orogeny caused little or no ductile deformation in the Archean basement in the Negaunee area.

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INTRODUCTION

The Negaunee area of Michigan's Upper Peninsula (fig. 1) contains good local exposures of both Archean and Early Proterozoic rocks. The Archean rocks, which are the focus of this study, are part of the Ishpeming greenstone belt of the Archean northern complex (see Morgan and DeCristoforo, 1980) and are among the southernmost exposures of metavolcanic and metasedimentary rocks of the Superior province of the Canadian Shield (Card and Ciesielski, 1986). The Early Proterozoic metasedimentary rocks in this area occupy broad basins that overlie the Archean basement rocks, and they were deformed during the Early Proterozoic Penokean orogeny (approximately 1,850 Ma) (Cannon, 1973).

Several workers (for example, Cannon and Klasner, 1972; Klasner, 1972, 1978; Cannon, 1973; Klasner and others, 1988) have proposed thin-skinned deformation models to explain the strong regional deformation fabrics in the Early Proterozoic rocks and, in part, to explain their juxtaposition with Archean rocks. They suggested that a decollement exists between the Archean and Early Proterozoic rocks because of differences in the style of deformation between the Early Proterozoic rocks and the underlying Archean rocks. Recent work, however, has led to the recognition of two distinct and widely separated structural regimes in the Early Proterozoic rocks of northern Michigan (Klasner and others, 1988; Klasner and others, 1991; Klasner and Sims, 1992): (1) a foreland thrust belt in the north, in which Penokean deformation was largely thin skinned, and (2) an imbricate fold and thrust belt in the south, which is part of

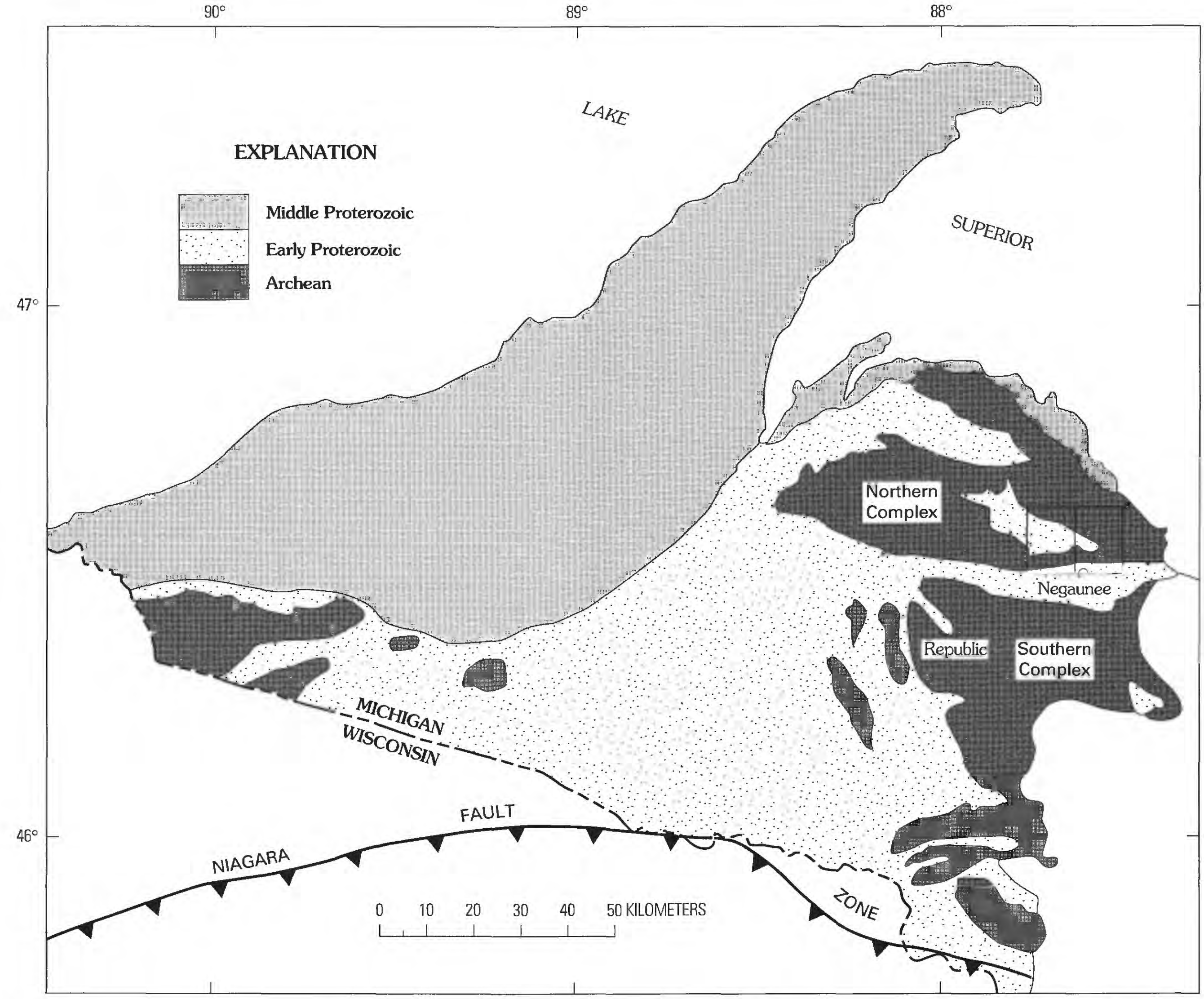


Figure 1. Distribution of Precambrian rocks in the western Upper Peninsula of Michigan (modified from Puffett, 1974). Boxes outline the Negaunee SW (left) and Negaunee (right) quadrangles of this study. On Niagara fault zone, sawteeth on overthrust block.

a broad basement arch in which deformation involved both Archean basement and Early Proterozoic supracrustal rocks.

Although thick-skinned Early Proterozoic deformation has been documented in Archean rocks of the southern complex (fig. 1), separating Archean from Early Proterozoic deformation within the Archean basement rocks in the northern complex is complicated. This is because the major deformation fabrics (Puffett, 1974; Clark and others, 1975) and the finite strain axes (Westjohn, 1978, 1986, 1987; Meyers, 1983; Carter, 1989) in both Archean and Early Proterozoic rocks of the area are subparallel. Based only on these regional fabrics, one might conclude that Penokean orogenic activity was thick skinned, characterized by pervasive ductile deformation of Archean basement rocks. Even though regional deformation of the Early Proterozoic rocks in the Negaunee area is well documented (for example, Cannon, 1973; Klasner, 1978, 1972; Klasner and others, 1988; Klasner and others, 1991), detailed structural studies in the Archean rocks of the area have not been made. This report presents a detailed analysis of small-scale deformation structures, deformation fabrics, and finite strain in several of the Archean rock units. It was aided considerably by published geologic maps of the Archean rocks of the region (such as Gair and Thaden, 1968; Puffett, 1974; Clark and others, 1975), which provided an excellent geologic base for our more detailed structural analysis.

The primary objectives of our structural studies were (1) to develop a structural model that is consistent with the kinematic framework indicated by ductile to brittle-ductile deformation features in the Archean rocks of the Negaunee area, and (2) to evaluate the relationship of this deformation to that in the adjacent Early Proterozoic rocks. To pursue these objectives, we analyzed deformation fabrics and finite strains within selected regions of the Archean rock exposures in the Negaunee area that are adjacent to deformed Early Proterozoic rocks of the Dead River basin and the Marquette trough (fig. 2). We also analyzed the geometry of an Early Proterozoic fold adjacent to the Archean rocks, which we used as a local standard for Early Proterozoic deformation.

The analysis presented in this report indicates that the Archean rocks of the Negaunee area contain deformation features associated with four Archean deformation episodes (D_1, D_2, D_3, and D_4). The most widespread and penetrative deformation (D_2) produced a regional foliation (S_2) in the Ishpeming greenstone belt (Archean rocks north of the Marquette trough, fig. 2). Although the S_2 foliation and D_2 finite strain axes have orientations similar to those in adjacent Early Proterozoic rocks, post-D_2 deformation features in the Archean rocks—such as D_3 dip-slip shears and D_4 kink bands, strike-slip shears and crenulations—indicate reorientation of the regional principal stress axes during the late stages of the orogenesis recorded in the Archean rocks. Because these structures are not recognized in Early Proterozoic rocks, they predate the Early Proterozoic deformation. We conclude that the Early Proterozoic Penokean orogeny imposed little or no ductile deformation on the previously deformed Archean rocks in the Negaunee area.

REGIONAL GEOLOGY AND TECTONIC FRAMEWORK

Archean

The Archean rocks within the region are part of the Ishpeming greenstone belt (Morgan and DeCristoforo, 1980) and consist mainly of metasedimentary rocks, felsic metavolcanic rocks, and metabasalts that are intruded by felsic plutons and local mafic and ultramafic bodies. These Archean rocks occur as nearly vertical easterly striking units (fig. 2) that are locally truncated by brittle to brittle-ductile faults of both Archean and Early Proterozoic age. Large-scale recumbent folds that are refolded by upright, east-west-trending folds have been recognized in northern parts of the Ishpeming greenstone belt (Johnson and Bornhorst, 1991; Johnson, 1990); however, early recumbent structures have not been recognized in the Negaunee area.

Sims (1980) and Sims and others (1980) have suggested that the Ishpeming greenstone belt is an extension of the greenstone-granite terrane of Minnesota (Wawa subprovince) that lies north of the major Archean crustal boundary known as the Great Lakes tectonic zone (GLTZ). The GLTZ is a regional Archean suture zone extending from the central Dakotas eastward across central Minnesota, northern Wisconsin, and Upper Michigan. It is a zone of tectonism, first recognized in central Minnesota, that is associated with the suturing of a northern greenstone-granite terrane and a southern gneissic terrane (Morey and Sims, 1976; Sims, 1991).

The Late Archean greenstone-granite terrane yields radiogenic ages of 2.6–2.8 Ga (Peterman, 1979), whereas the Middle Archean gneissic terrane yields ages as old as 3.0–3.8 Ga (Goldich and others, 1970; Sims and Peterman, 1976; Peterman, 1979; Sims and others, 1980). U-Pb isotopic ages from the metavolcanic and granitic rocks of the northern complex are about 2.75 Ga (Hammond and Van Schmus, 1978), and are consistent with those derived from other parts of the greenstone-granite terrane. The southern complex is interpreted to lie south of the GLTZ and primarily to be part of the gneiss terrane (see Sims, 1991), but no rocks in the southern complex have been found with isotopic ages as old as 3.0–3.8 Ga.

Early Proterozoic

Early Proterozoic metasedimentary rocks of the Marquette Range Supergroup were deformed during the Penokean orogeny (approximately 1.85 Ga). These rocks represent an extensive continental margin assemblage (Cambray, 1978) that is truncated on the south by the Niagara fault zone (Van Schmus, 1976; Klasner and others, 1988; Sims, 1990) (fig. 1), a broad zone of shearing and highly flattened rocks as much as 10 km wide (Klasner and others, 1988) that separates the northern continental margin assemblage from a southern magmatic arc terrane (Van Schmus, 1976; Sims and others, 1989). Sedlock and Larue (1985) interpreted the Niagara fault zone as a 1.85 Ga suture zone associated with the development of the Penokean fold belt in Upper Michigan and Wisconsin.

Deformation of the Early Proterozoic rocks in the Negaunee area is relatively simple compared to that imposed on rocks of this age near the Niagara fault zone. Most of the deformation fabrics are associated with upright folding. In the sparse outcrops exposing the contact between the Early Proterozoic rocks and the Archean rocks of the northern complex, the rocks are deformed in a brittle fashion and contain a cataclastic fabric (Gair and Thaden, 1968). Klasner and others (1988) suggested that these brittle structures were formed during the late stages of the Penokean orogenesis and are associated with vertical tectonic stresses resulting from block uplifts.

ROCK UNITS AND LITHOLOGIES

Precambrian rocks in the Negaunee area were first mapped and described by the U.S. Geological Survey in the late 19th century (Williams, 1890; Van Hise and Bayley, 1895; Van Hise and others, 1897). During more recent mapping (Gair and Thaden, 1968; Puffett, 1974; Clark and others, 1975), the units were remapped and their stratigraphic nomenclature was revised. The stratigraphy in

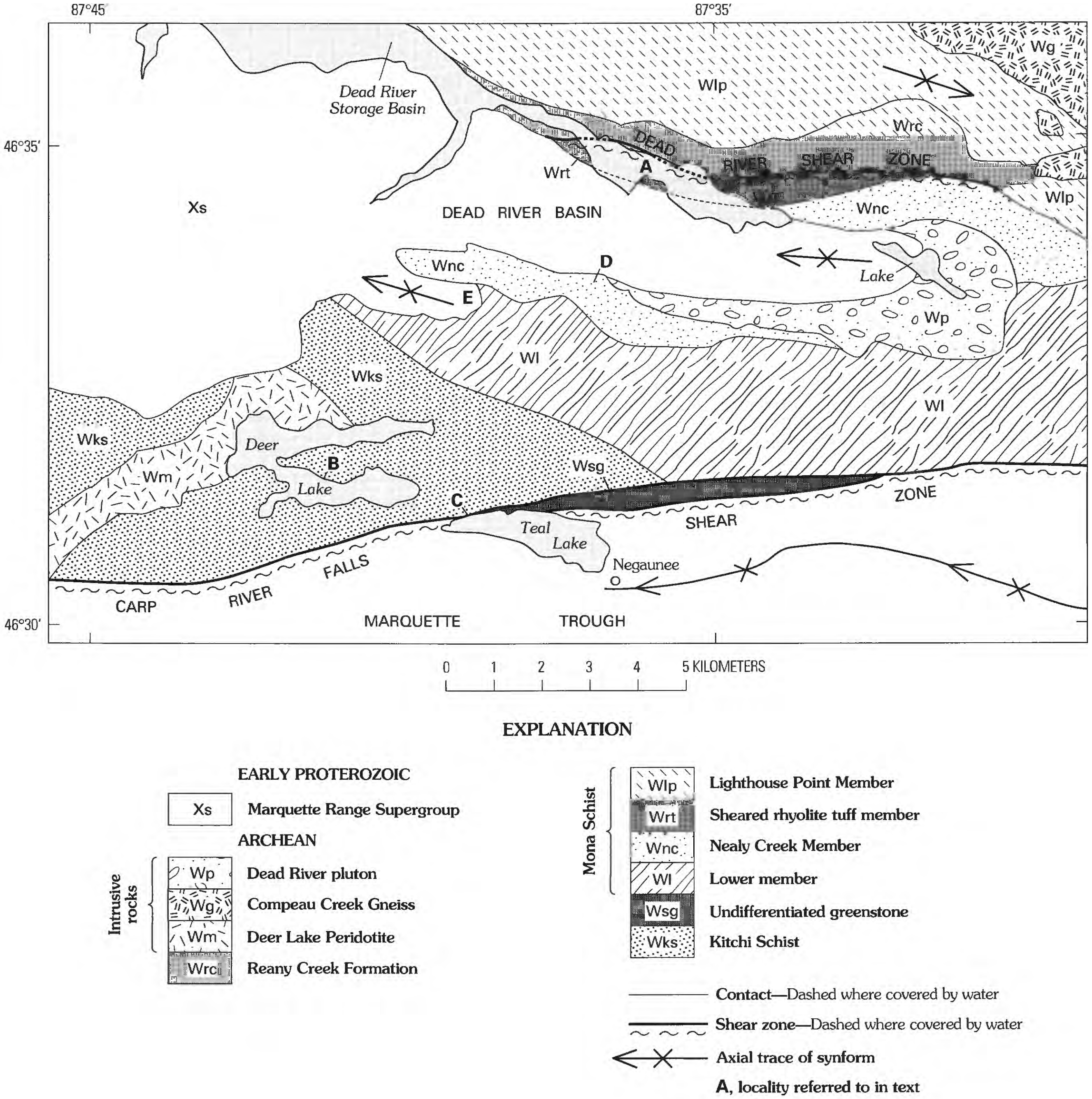


Figure 2. Geology of the southern two-thirds of the Negaunee SW and Negaunee quadrangles. Letters A–E are outcrop localities described in the text. (Modified from Puffett, 1974, and Clark and others, 1975.)

this report is consistent with that of more recent studies, except for Johnson and Bornhorst (1991). Johnson and Bornhorst have proposed that the Lighthouse Point Member of the Mona Schist be redefined as the Lighthouse Point Basalt, of formational status. They continue to consider the rocks south of the Dead River shear zone (fig. 2) as part of the Mona Schist restricted. In this report, we use the nomenclature of Puffett (1974) and Clark and others (1975). The mapped distribution of these units is shown in figure 2.

Archean Rocks

Kitchi Schist

The Kitchi Schist (unit Wks, fig. 2) comprises felsic metavolcanic rocks and amphibolite. The Carp River Falls shear zone truncates the southern boundary of the unit, adjacent to the Early Proterozoic metasedimentary rocks of the Marquette trough, and the Dead River basin defines part of its northern boundary (figs. 2, 3). The nature of the northeastern contact of the Kitchi Schist with the Mona Schist is unclear (see discussion following). Van Hise and Bayley (1895) named and first described the Kitchi Schist; Morgan and DeCristoforo (1980) subsequently subdivided it into amphibolite units and intermediate to felsic metavolcanic units. The relatively undeformed amphibolitic units (to the northwest) and the felsic metavolcanic units are separated by the northeast-trending ultramafic intrusive unit—the Deer Lake Peridotite (fig. 2). The felsic metavolcanic rocks are dacitic to andesitic in composition and are locally intercalated with agglomerates. Puffett (1974) suggested that these rocks consist of subaerially deposited ash flows and that the agglomerates are more felsic pyroclasts.

Mona Schist

The Mona Schist, named by Van Hise and Bayley (1895), was subdivided by Gair and Thaden (1968) into a lower member consisting mostly of metabasalt interlayered with lesser amounts of metagabbro, metadiabase, and metapyroxenite, and upper members consisting of felsic pyroclastic rocks and rhyolite dikes. The south margin of the Mona Schist is bounded by the Carp River Falls shear zone (fig. 2) (Puffett, 1974) and is in structural contact with Early Proterozoic metasedimentary rocks of the Marquette trough (fig. 2). The southwest margin is marked by a contact of uncertain origin with the Kitchi Schist. (See Puffett, 1974; Clark and others, 1975.)

Gair and Thaden (1968) and Puffett (1974) suggested that the lower member (unit Wl, fig. 2) is the oldest unit of the Mona Schist because the stratigraphic topping directions obtained from cusps of the pillowed metabasalts in the unit are consistently northward. However, the relative age relationship of the lower member of the Mona Schist and the adjacent Kitchi Schist is uncertain. Morgan and DeCristoforo (1980) suggested that the two units were deposited or emplaced during two different Archean volcanic cycles, with the lower member being the youngest because it unconformably overlies the Kitchi Schist. However, Puffett (1974) suggested that the relative ages of the lower member of the Mona Schist and the Kitchi Schist cannot be determined because of the poor exposure of their contact. Clark and others (1975) mapped this contact as a shear zone.

The upper part of the Mona Schist was subdivided by Puffett (1974) into the Nealy Creek Member (unit Wnc, fig. 2), the sheared rhyolite tuff member (unit Wrt, fig. 2), and the Lighthouse Point Member (unit Wlp, fig. 2). The Nealy Creek Member, exposed both north and south of the Dead River Storage Basin (fig. 2), is a fine-grained, massive, sericitic schist and contains local compositional layering (S_0). Gair and Thaden (1968) and Puffett (1974) suggested that the Nealy Creek Member is a subaerially deposited, felsic-pyroclastic unit because of its dacitic composition and because it contains some pyroclasts. The unit also contains pelitic and psammitic metasedimentary rocks.

The sheared rhyolite tuff member of the Mona Schist (fig. 2) was mapped by Puffett (1974) as a broad zone of sheared rocks. In a detailed study of relative age and petrologic and geochemical relationships of rocks in the sheared rhyolite tuff member, MacClellan and Bornhorst (1989) concluded that rock units of different relative ages within this member are deformed differently. They described three different components of this unit: (1) a "rhyolite," designated here as type-a rhyolite, (2) an "undifferentiated foliated pillowed basalt," and (3) a "highly foliated rhyolite," designated here as type-b rhyolite. The type-a and type-b designations are arbitrarily chosen for this report to avoid possible confusion in later discussions of these rock units and because both of the rhyolites are locally foliated. The sheared rhyolite tuff member consists mainly of the type-b rhyolite. This unit, which locally is clearly a tuff, agglomerate, or volcanogenic metasediment, is a quartz-sericite schist containing quartz and plagioclase phenocrysts or clasts that are aligned in the foliation (Puffett, 1974; MacClellan and Bornhorst, 1989). The type-a rhyolite also has quartz and plagioclase phenocrysts, but it intrudes the type-b rhyolite. MacClellan and Bornhorst (1989) suggested that the type-a rhyolite correlates with the intrusive rhyolite of Fire Center mine located about 1 km north of the Dead River Storage Basin. (See Owens and Bornhorst, 1985; Johnson and others, 1986.) The rhyolite of the Fire Center mine is interpreted as an Archean intrusive rock because it crosscuts the volcanic rocks of the Lighthouse Point Member (discussed following) (fig. 2) but does not crosscut the Late Archean Reany Creek Formation (MacClellan and Bornhorst, 1989).

The Lighthouse Point Member of the Mona Schist consists of layered amphibolite and felsic pyroclastic rocks with subordinate intercalated chert and iron-formation (Morgan and DeCristoforo, 1980; Owens and Bornhorst, 1985; MacClellan and Bornhorst, 1989). The oldest and most voluminous rocks of this unit are amphibolites. Morgan and DeCristoforo (1980) suggested that these are pillowed basalt locally intruded by gabbro. Van Schmus (1974) obtained a Rb-Sr age of 2.75 Ga from a felsic tuff in this unit, but its age relative to other Archean rocks in the Ishpeming greenstone belt is not firmly established. Johnson and Bornhorst (1991) have described the nature and geometries of the deformational features in this unit.

Undifferentiated Greenstone

Puffett (1974) mapped a fault-bounded block of metaamphibolites, with lesser amounts of felsic metavolcanic rocks and gray sericitic shale, as undifferentiated greenstone (unit Wsg, fig. 2). This unit is strongly sheared and contains parts of the adjacent greenstone belt as well as Proterozoic metasedimentary rocks from the Marquette trough.

Compeau Creek Gneiss

The Compeau Creek Gneiss (unit Wg, fig. 2) is a variably foliated rock that ranges from tonalite to granite in composition (Puffett, 1974). This unit was first named and described by Gair and Thaden (1968), who observed that it intrudes parts of the Ishpeming greenstone belt. It is typically well foliated along its contact with wall rocks but is less foliated within interior parts of the unit.

Dead River Pluton

The Dead River pluton (unit Wp, fig. 2) consists of comagmatic syenite, diorite, and granodiorite (Puffett, 1974; MacClellan and Bornhorst, 1989) that are relatively unfoliated. Attempts to date this unit radiometrically have been unsuccessful (Van Schmus, 1974); however, it is interpreted to be of Late Archean age because of its nonconformable contact with adjacent Early Proterozoic metasedimentary rocks (Puffett, 1974).

Reany Creek Formation

Puffett (1974) described the Reany Creek Formation (unit Wrc, fig. 2) as consisting of a basal conglomerate, a middle chloritic shale, and an upper unit of interbedded conglomerate, slaty graywacke, and horizons of quartzite and arkose. The clasts within the unit are derived from parts of the granite-greenstone belt, and consist mostly of light-colored felsic intrusive rocks from the adjacent Dead River pluton. Puffett (1969) suggested that the clasts are dropstones, indicating that the deposit has a glacial origin during the Early Proterozoic. Sims (1991), however, believes that the unit was deposited in a fault-bounded transtensional basin (compare Norris and Carter, 1982) developed during Late Archean time.

Early Proterozoic Rocks

In parts of Upper Michigan, Early Proterozoic metasedimentary rocks of the Marquette Range Supergroup (Cannon and Gair, 1970) occupy broad, linear basins (fig. 1) that overlie Archean rocks. These Early Proterozoic rocks (unit Xs, fig. 2) are composed mainly of slate, metaquartzite, marble, and intercalated iron-formation that were deposited along a rifted continental margin prior to the Penokean orogeny (Van Schmus, 1976; Cambray, 1978; Sedlock and Larue, 1985; Klasner and others, 1988). The principal rock units exposed in the study area include the Ajibik Quartzite, Goodrich Quartzite, and Michigamme Formation (Clark and others, 1975; Puffett, 1974).

Metamorphism

Archean rocks in the Ishpeming greenstone belt contain mineral assemblages consistent with greenschist-facies metamorphic conditions in the southern part of the belt (Puffett, 1974) and amphibolite-facies metamorphic conditions in the northern part of the belt (Johnson and Bornhorst, 1991). All Archean rocks in our study area are within the greenschist-facies part of the belt.

The Early Proterozoic rocks of the study area lie in the chlorite zone (greenschist facies) of the Republic node of regional metamorphism of James (1955), which reached sillimanite grade (amphibolite facies) about 17 km to the west of the study area. Studies of the relationship between growth of metamorphic minerals and deformation have been done by Klasner (1972, 1978), primarily in pelitic rocks of the Marquette Range Supergroup (Cannon and Gair, 1970). Klasner showed that peak metamorphism postdated the formation of the regional west-northwest-trending structural fabric in the Early Proterozoic strata.

STRUCTURAL FEATURES AND THEIR GEOMETRIES

Structural Correlation with Adjacent Areas

Recent mapping and structural analysis of Archean metabasalt in the Ishpeming greenstone belt north of the Negaunee area show that these rocks were deformed during at least two phases of Archean folding (Johnson, 1990; Johnson and Bornhorst, 1991). The earliest deformation (D_1) is characterized by kilometer-scale recumbent folds (F_1) in tholeiitic basalt. These F_1 folds have west- to northwest-trending axial traces and shallow, easterly plunging hinge lines (Puffett, 1974; Johnson, 1990; Johnson and Bornhorst, 1991). Johnson (1990) described a second deformation (D_2) north of the Negaunee area that folds a flat-lying foliation (S_1) that is axial-planar to F_1 recumbent folds. These F_2 folds are widespread in the area; they are upright with nearly vertical, west-striking axial planes and contain a locally well developed S_2 axial-plane foliation.

We have not recognized F_1 folds in the Negaunee area, although the S_1 foliation is locally developed in the Lighthouse Point Member of the Mona Schist in the northern part of the area. The most widespread deformation fabric in the Negaunee area is the steeply dipping west-northwest-striking foliation that we correlate with the S_2 foliation of Johnson and Bornhorst (1991). However, structural features and their geometries examined during our study (table 1) define two additional stages of deformation (D_3 and D_4). In the following section, we describe the deformation geometries and fabrics associated with each of these deformations in selected structural domains.

Structural Domains and Analyzed Features

Three individual domains (fig. 3) were chosen for detailed structural analysis and strain analyses of Archean

Table 1. Deformation events affecting the Archean rocks of the Negaunee area

Event	Locations/Domains	Characteristics
D_1	Domain III	F_1: recumbent folds; S_1: flat-lying foliation.
D_2	Domains I, II, and III	F_2: upright folds and crenulations; S_2: regional near-vertical west-northwest foliation.
D_3	Carp River Falls shear zone and Dead River shear zone, mostly.	East-west trending, dip-slip, north-side-up, brittle/ductile shear zones. S_3 (C) foliation.
D_4	Domains I, II, and III	Kink bands, crenulations; strike-slip shearing.

rocks; part of one of these domains (domain II) was also examined to evaluate the structural geometries in the adjacent Early Proterozoic rocks. Domain I, located in the southern part of the Negaunee SW quadrangle (fig. 1), north of the Marquette trough and south of the Dead River basin, contains a well-developed S_2 foliation and a locally well developed S_3 shear foliation associated with the Carp River Falls shear zone. Domain II includes exposures of adjacent Archean and Early Proterozoic rocks along the south margin of the Dead River basin. The Archean rocks of this domain contain local F_2 folds and a well-developed S_2 foliation that is locally cut by D_3 shear zones and deformed by D_4 crenulations and kink bands. The Early Proterozoic rocks of domain II have been folded by a west-northwest-plunging syncline (fig. 2) that is not evident in the adjacent Archean rocks. Domain III, in the northern part of the Negaunee quadrangle along the north margin of the Dead River basin, contains local F_2 folds and crenulations and a well-developed S_2 foliation that is deformed by D_3 shearing associated with the Dead River shear zone. The deformation features in these domains are described in the following sections in their approximate age order of deformation.

Regional S_2 Foliation and F_2 Folding

Domain I

The Kitchi Schist in domain I contains both felsic metavolcanic and mafic amphibolite units. The felsic metavolcanic rocks are primarily tuffaceous, but include local agglomerates. The felsic units contain a weak to moderate S to L–S fabric that predates the Carp River Falls shear zone. However, the amphibolite units of the Kitchi Schist (northwest of the area of the Deer Lake Peridotite, fig. 2) show little or no deformation fabric and were clearly more competent than the felsic units during deformation (Morgan and DeCristoforo, 1980). Alignment of platy minerals in the felsic rocks, mainly chlorite, defines a west-northwest-striking nearly vertical S_2 foliation (fig. 4*A*).

The matrix of the felsic agglomerate rocks in domain I sustained more deformation than the matrix-supported felsic clasts. Felsic clasts are composed mostly of sericite with lesser amounts of albitic plagioclase. Strain shadows, defined by elongate clusters of quartz + calcite ± chlorite, occur extensively on the termini of the felsic clasts in a nearly vertical orientation. The orientation of the clast and their strain shadows indicate that tectonic elongation was nearly vertical during the development of S_2 foliation.

Domain II

The metavolcanic and metasedimentary rocks of Archean Nealy Creek in domain II contain a well-developed, penetrative subvertical S_2 foliation that generally strikes west-northwest (fig. 4*B*). The foliation is locally crenulated and kinked, but these structures were formed during late-stage deformations.

Domain III

Features of deformation D_2 in domain III include well-developed F_2 folds, crenulations, and an associated axial-planar S_2 foliation. The dominant S_2 foliation within domain III is nearly vertical and strikes east (fig. 4*C*). Sparse, shallowly plunging F_2 crenulations of S_0 and S_1 occur in the Nealy Creek Member of the Mona Schist in this domain. The crenulations are typically asymmetrical microfolds with wavelengths from 1 to 10 mm. The axial planes of the crenulations are parallel to both the regional nearly vertical, west-northwest-striking S_2 foliation and the axial planes of larger scale F_2 folds. A well-developed S_2 foliation that is axial-planar to the crenulations is present in many samples and occurs in two forms (see fig. 5). The first is a spaced foliation that ranges from slightly anastomosing to smooth (compare Powell, 1978) and contains thin layers of dark, insoluble residue indicative of a pressure solution

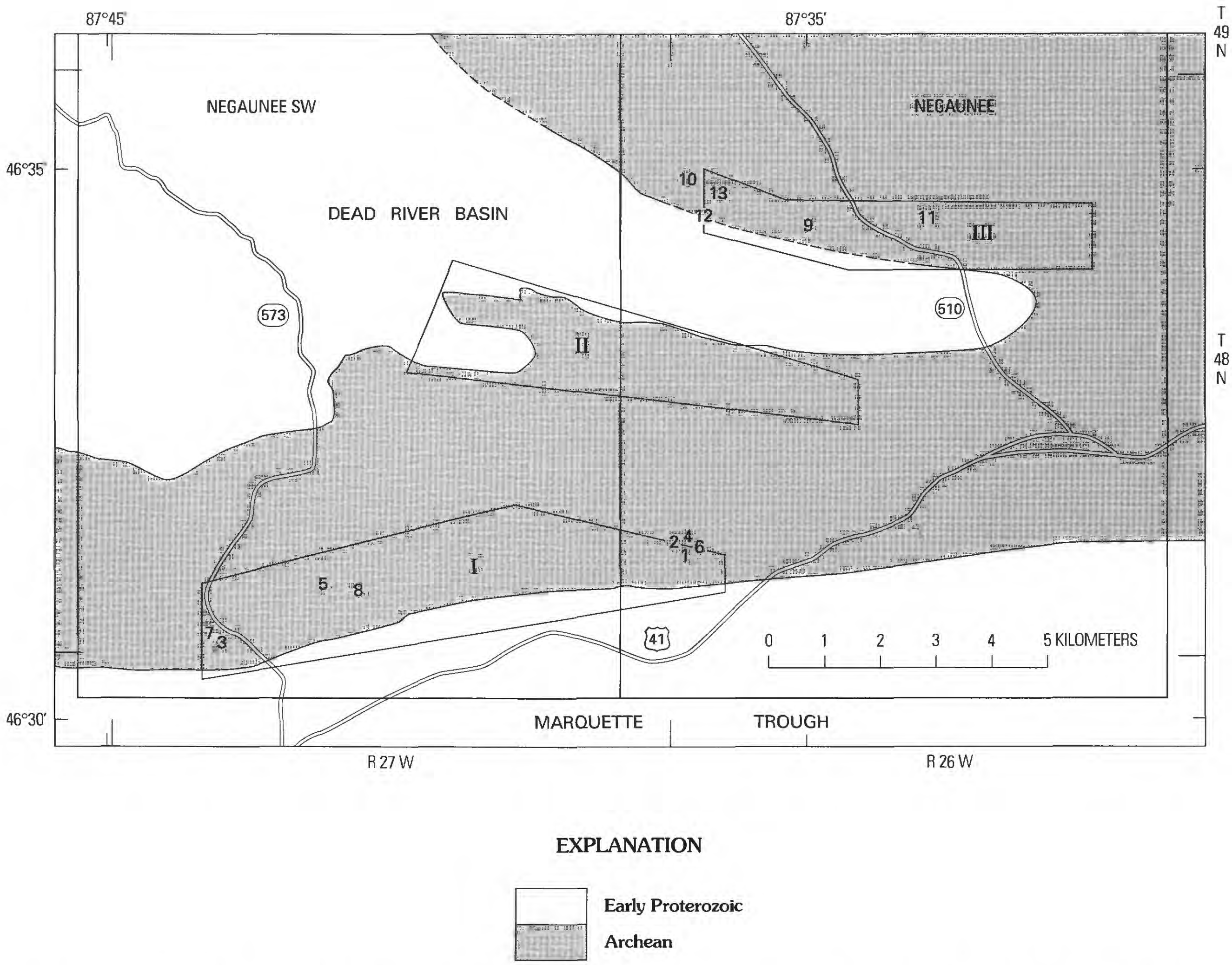


Figure 3. Distribution of structural domains I, II, and III of this study. Numbers are localities from which strain analyses were obtained. Contact dashed where approximate.

origin (right side of fig. 5). The second is a zonal to incipient zonal crenulation cleavage (compare Gray, 1977; Powell, 1978) that is variably developed on the short limbs of asymmetrical crenulations (left side of fig. 5). S_2 is also axial-planar to sparse, open to isoclinal upright folds (F_2) of primary compositional layering (S_0) (fig. 4*D*). The axial planes of these shallowly to steeply plunging F_2 folds are nearly vertical and strike east-northeast (fig. 4*D*).

Figure 6 shows an example of symmetrical F_2 folds in the undifferentiated foliated pillow basalt within the sheared rhyolite tuff member of the Mona Schist (locality A, fig. 2). The metabasalt is intensely folded by 10-cm- to 1-m-amplitude F_2 folds that range from close to isoclinal. Type-a rhyolite dikes intrude the foliated pillow basalt but are not folded.

Most of the strong foliation within both the type-a and type-b rhyolites of the sheared rhyolite tuff member of the Mona Schist developed in response to localized shearing (Puffett, 1974; discussed following) rather than regional D_2 shortening.

D_3 North-Side-Up, Dip-Slip Shear Zones

Distribution and Timing of D_3 Shearing

Two major brittle-ductile shear zones within the study area, the Carp River Falls shear zone (CRFSZ) (domain I) and the Dead River shear zone (DRSZ) (domain III) (figs. 2, 3, 7), are nearly vertical shear zones that may have been initiated during the early stages of deformation (D_1 or D_2) in the Ishpeming greenstone belt. However, inasmuch as an S_3 shear foliation locally cuts both the earlier S_2 foliation and upright F_2 folds, a significant component of deformation along these (D_3) shear zones clearly occurred after D_2. Kinematic indicators within the shear zones, such as rotated

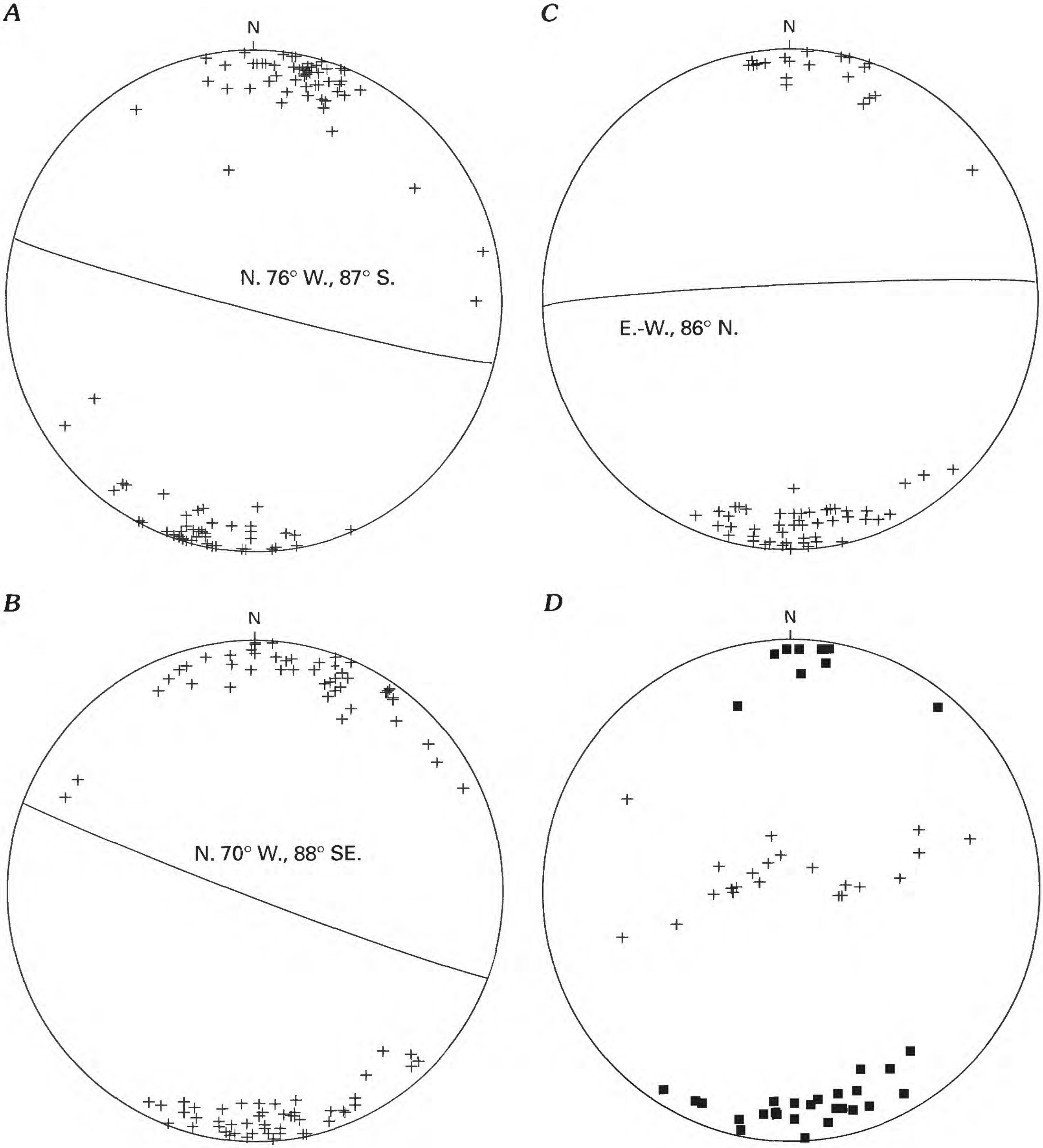


Figure 4. Equal-area projections of D_2 fabric elements in the Negaunee area. Great circles indicate the average S_2 orientation, defined as the plane normal to the highest contoured concentration of plotted poles to S_2. *A*, Poles to S_2 foliation (n=82) from the Kitchi Schist (felsic metavolcanic rocks) in domain I. *B*, Poles to S_2 foliation (n=81) from domain II. *C*, Poles to S_2 foliation (n=69) from domain III. *D*, Poles to F_2 fold axial planes (solid squares, n=35) and F_2 fold hinge lines (crosses, n=23) from domain III.

asymmetrical porphyroclasts and asymmetrical tension veins, are consistent with north-side-up relative displacements. These shear zones were locally reactivated during both Archean D_4 deformation and Early Proterozoic deformation (Puffett, 1974; Bornhorst, 1988). Bornhorst (1988) concluded that the CRFSZ is an Archean structure because it is crosscut by less deformed Archean metadiabase dikes (Baxter and Bornhorst, 1988).

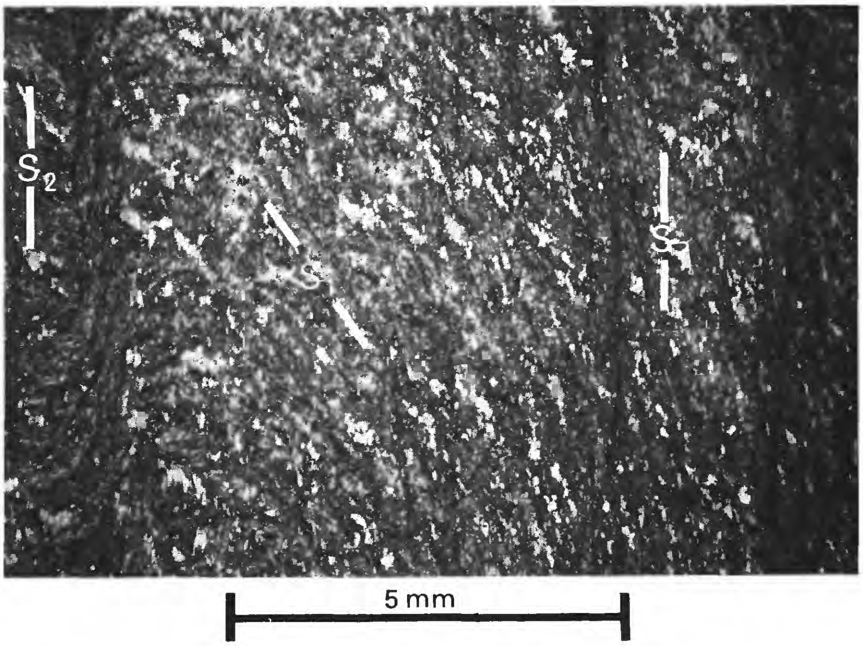


Figure 5. Photomicrograph (plane light) of upright F_2 crenulations of the S_1 foliation in the Nealy Creek Member of the Mona Schist in domain III. The section, cut normal to the nearly horizontal east-trending crenulation hinge line, contains an incipient zonal (nonpenetrative) S_2 crenulation cleavage (left side of photo) and a smooth disjunctive S_2 cleavage with dark lines of residue from pressure solution (right side of photo).

Figure 6. Close, upright, shallowly plunging F_2 folds in the undifferentiated foliated pillowed basalt from the sheared rhyolite tuff member of the Mona Schist (north shore of the Dead River Storage Basin, locality A in fig. 2). Hammer handle is 14 cm long. Arrow on photo indicates north.

Carp River Falls Shear Zone (Domain I)

The east-trending Carp River Falls shear zone (CRFSZ) truncates the southern boundaries of both the Kitchi Schist and the lower member of the Mona Schist (fig. 2), and juxtaposes Archean rocks to the north and Early Proterozoic rocks to the south.

Shear fabric and kinematic data were gathered from primarily three areas in domain I (figs. 2, 3): (1) within the shear zone itself, (2) along the northeast shoreline of the southern segment of Deer Lake (locality B, fig. 2), and (3) northwest of Teal Lake (locality C, fig. 2). The orientation of poles to the S_3 shear foliation (C planes of Lister and Snoke, 1984), shown in figure 7*A*, is subparallel to the regional S_2 foliation in domain I. (See fig. 4*A*.) These three shear zone areas, defined by well-developed phyllonitic fabrics, are most commonly confined to topographic depressions, and they are marked by deposition of carbonate minerals and quartz (Puffett, 1974) associated with hydrothermal alteration.

An excellent exposure of sheared rock within domain I occurs along the northeast shore of the southern part of Deer Lake (locality B, fig. 2). In this area, a conspicuous east-trending topographic low, approximately 30 m wide, defines the trace of a shear zone and contains phyllonites whose fabrics become stronger toward the center of the zone.

Rotated en-echelon tension veins in sheared rocks containing a strong planar fabric indicate north-side-up, dip-slip relative displacement (fig. 8). C-foliations (S_3) occur in the most strongly deformed parts of the shear zone. Agglomeratic clasts seem to be lacking in these strongly deformed areas, perhaps because they were destroyed by the large localized shear strains. The clasts in less deformed parts of the shear zone are elongated vertically.

Sheared Archean metavolcanic rocks within the mapped area of the CRFSZ are well exposed near the northwest shore of Teal Lake (locality C, fig. 2), and contain brittle-ductile kinematic indicators, such as asymmetrical agglomerate clasts, indicating north-side-up, dip-slip shear. This zone was also reactivated during the Penokean orogeny (Bornhorst, 1988), which produced brittle shears in the Archean rocks along the fault zone.

Shear zones of D_3 within the Kitchi Schist northeast of Teal Lake also indicate north-side-up, dip-slip shearing (localities 1, 2, 4, and 6, fig. 3). Kinematic indicators in the shear zones include asymmetrical strain shadows on porphyroclasts (compare Passchier and Simpson, 1986), shear bands (compare Lister and Snoke, 1984), and rotated tension veins. Figure 9 is a photomicrograph of a sheared pyrite porphyroclast from this particular shear zone. Asymmetrical quartz-filled strain shadows that were precipitated in areas of relatively low pressure during the noncoaxial deformation occur on the termini of the porphyroclast within the plane of S_3 shear foliation. The sigmoidal shape of the quartz and chlorite grains is further confirmation of the noncoaxial strain imposed on these rocks.

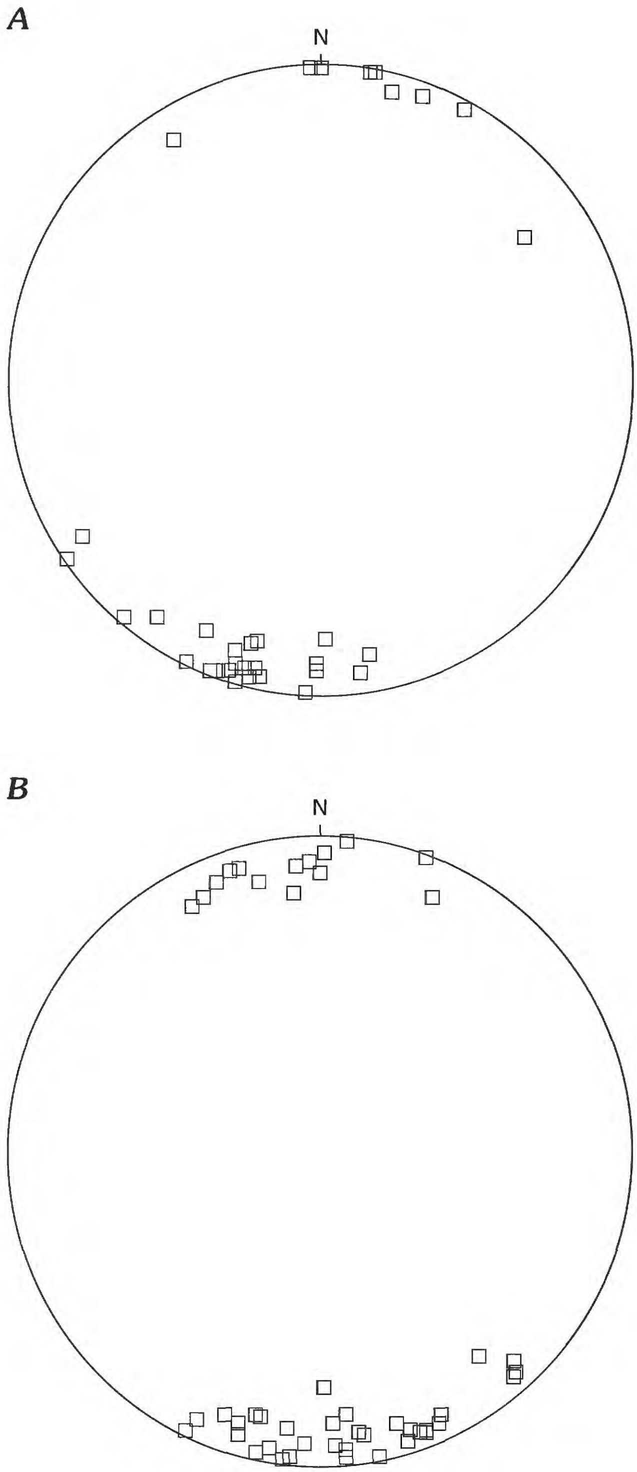


Figure 7. Equal-area projections of poles to S_3 shear foliation (C planes) from *A*, domain I in Carp River Falls shear zone (n=33), and *B*, domain III in Dead River shear zone (n=48).

Figure 8. D_3 en-echelon tension veins; barbs demonstrate dextral shear in plane of photograph. Actual D_3 shear within the shear plane is north-side-up within the Kitchi Schist (north lobe of southern part of Deer Lake, locality B, fig. 2). Arrow indicates north.

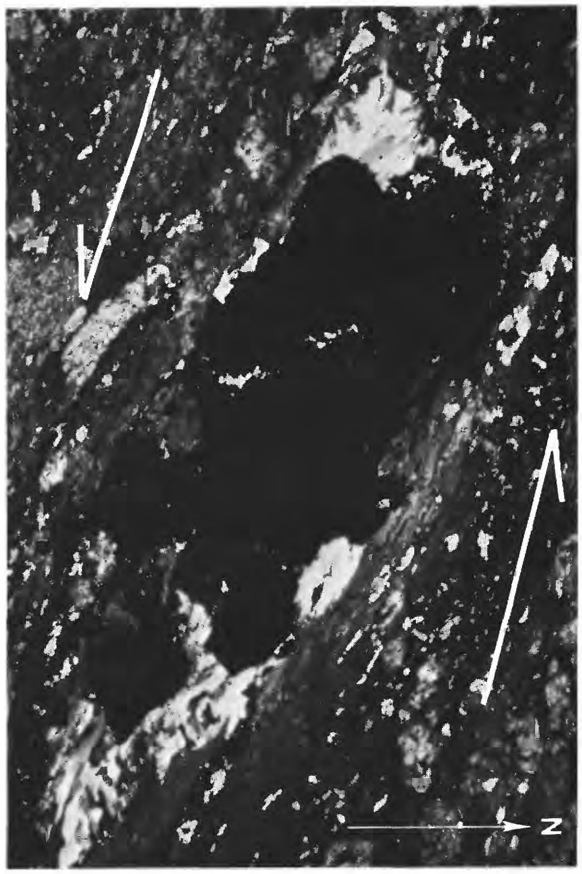


Figure 9. Photomicrograph (crossed nicols) of asymmetrical pyrite porphyroclast with asymmetric strain shadows of quartz that indicate sinistral (north-side-up) shear (see photomicrograph orientation markings). The shear sense barbs are parallel to the subvertical S_3, C foliation. The pyrite grain is approximately 1 cm long. Sample collected from S½ sec. 10, T. 48 N., R. 26 W., north of Teal Lake.

Dead River Shear Zone (Domain III)

The Dead River shear zone (DRSZ) (fig. 2) is a structure that we believe sustained most of its early deformation during D_3 and D_4 events. Bornhorst (1988) has suggested that the DRSZ is a broad, regional shear zone that extends from the northwest margin of the Dead River basin to Marquette. MacClellan and Bornhorst (1989) and Johnson and Bornhorst (1991) have also suggested that initial displacements along the shear zone are Archean, and P.K. Sims (written commun., 1991) postulated that it accommodated some of the transtensional deformation associated with deposition of the Reany Creek Formation. Puffett (1974) has shown that the most recent movement along the shear zone occurred after deposition of the Early Proterozoic Michigamme Slate of the Marquette Range Supergroup and prior to intrusion of Middle Proterozoic diabase dikes.

The DRSZ contains deformation features indicating that shearing was brittle-ductile in nature. Fabrics range from strong S to L–S. The type-b rhyolite incorporates the strongest phyllonitic shear fabric, although metabasalts and the type-a rhyolite dikes are also sheared. Kinematic indicators, such as asymmetrical porphyroclasts and en-echelon tension veins, give evidence for both transcurrent shearing that we attribute to D_4 deformation (thus S_4) and dip-slip shears that we attribute to D_3 deformation.

D_3 Shear Zones in Domain II

Some areas within domain II (for example, locality D, fig. 2) contain well-foliated felsic metavolcanic rocks (unit Wnc) that show clear evidence of brittle-ductile shearing. Sigma-type asymmetrical porphyroclasts (Passchier and Simpson, 1986; Simpson, 1986) with asymmetrical pressure shadows indicate north-side-up shearing (fig. 10). The strain-shadow mineral assemblage consists of quartz and chlorite, whereas the matrix consists of white mica, biotite, chlorite, and quartz.

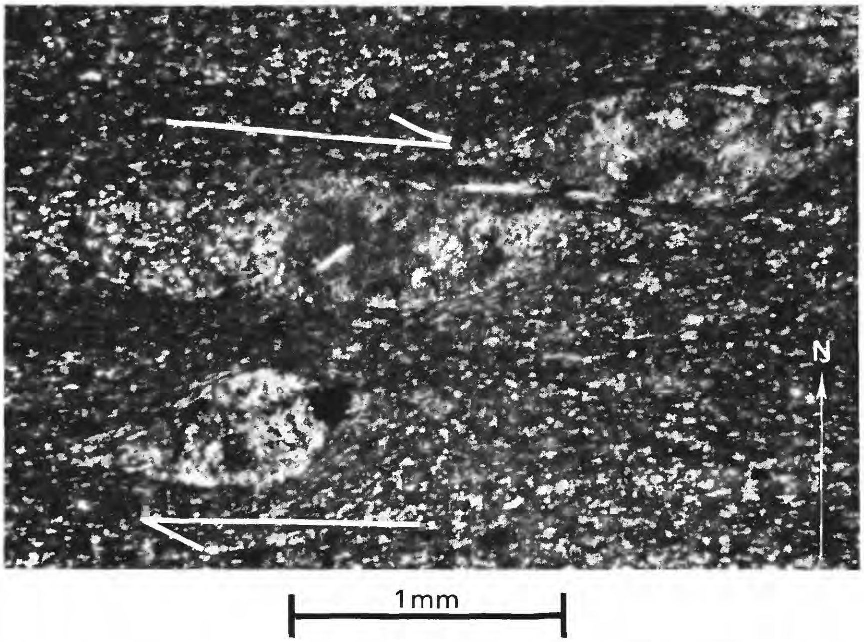


Figure 10. Photomicrograph (crossed nicols) of sigma-type porphyroclasts formed during D_3 shearing in the Nealy Creek Member of the Mona Schist along the contact of the Dead River pluton (domain III). Asymmetry of the porphyroclasts is consistent with dextral (north-side-up) displacement, indicated by barbs parallel to the subvertical S_3, C foliation. Sample collected from locality D (fig. 2).

D_4 Structures

The youngest brittle-ductile deformation (D_4) affecting Archean rocks of the study area deformed rocks that contained a well-developed S_2 foliation or S_3 foliation. Folding associated with this deformation includes widely distributed crenulations and local kink bands. These structures developed independent of and subsequent to D_3 as indicated by (1) kink bands and crenulations that deform D_3 fabrics, (2) D_4 shear features that indicate strike-slip relative displacements in contrast to D_3 structures that display dip-slip relative displacements, and (3) maximum principal stress direction inferred from D_4 kink bands being inconsistent with the moderately plunging, north-trending maximum principal stress axis associated with D_3 deformation. (See discussion in subsequent sections.)

D_4 Crenulations

D_4 crenulations are evident in the field as steeply plunging (fig. 11) linear ridges on well-developed S_2 or S_3 foliation planes. They occur in Archean rocks of all sites studied but are particularly well developed in metasedimentary and metavolcanic rocks of domains II and III that contain abundant sheet silicates. D_4 crenulations are always associated with D_4 kink bands, but they are much more common than the kink bands. These D_4 crenulations are most commonly asymmetrical with locally developed zonal crenulation cleavages. (See Gray, 1977, p. 768.) In some places, they occur as well-developed microbuckles with an associated discrete crenulation cleavage.

The type-a rhyolites of the sheared rhyolite tuff member of the Mona Schist contain D_4 crenulations that occur as closely spaced lineations on S_2 or S_3 foliation surfaces. The wavelength of these buckles is on the order of millimeters.

D_4 Kink Bands

D_4 kink bands are common in the sheared rhyolite tuff member of the Mona Schist (domain III), but they are less common in the Nealy Creek Member (domains II and III). Kink bands are associated with crenulations, but their morphology is distinct from the crenulations. The kink bands are defined by sharp angular displacements of S_2 or the S_3 C-foliation surfaces (fig. 12). The crenulations, in contrast, have smoothly curved hinge areas, and have the geometry of similar-type microfolds.

Kink bands may form as a result of layer-parallel shortening or layer-parallel extension. However, the occurrence of the D_4 kink bands locally as conjugate sets indicates that they are of contractional rather than extensional origin. (Compare Ramsay and Huber, 1987, p. 427.) The contractional origin of the kinks is also indicated by the equality of the angle between the kinked foliation and the kink plane (angle α) and the acute angle between conjugate kink planes (angle β) (fig. 13). Experiments conducted by Donath (1969) and Anderson (1974), in which highly foliated rocks were

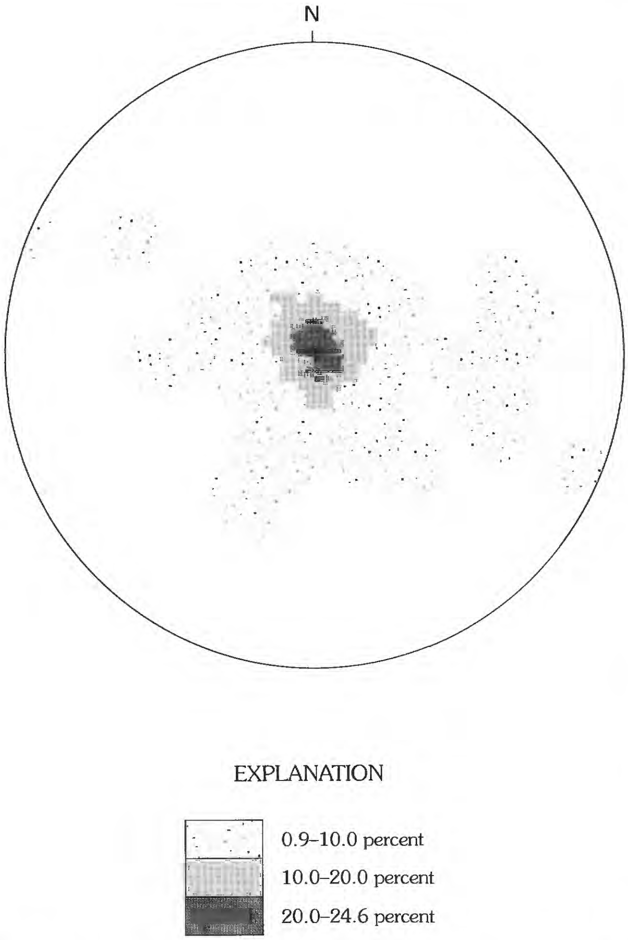


Figure 11. Contoured equal-area projection of orientations of D_4 crenulation hinge lines from all domains (n=112).

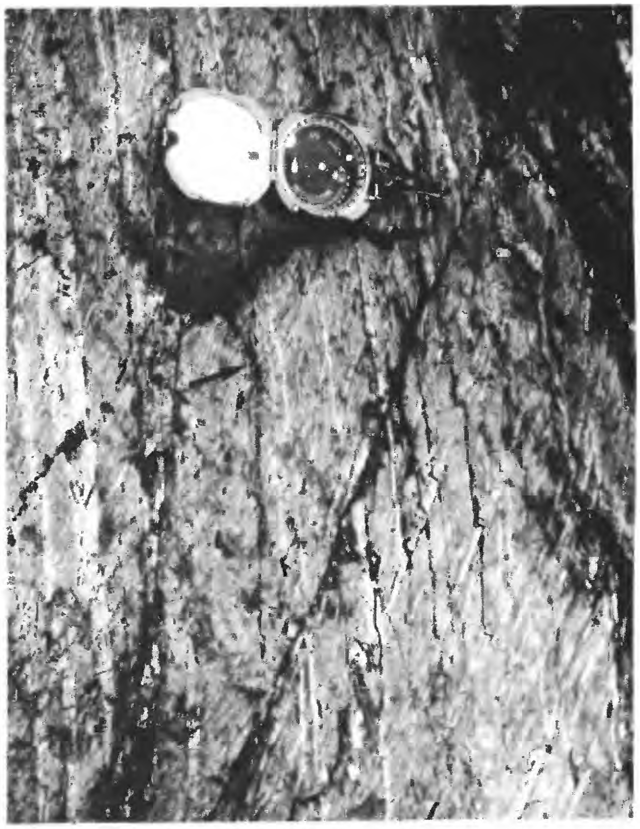


Figure 12. Well-developed S-symmetry kink bands in metasediment of the sheared rhyolite tuff member of the Mona Schist. The kinked foliation, S_2, is parallel to compositional layering (S_0) in the rock. Outcrop is on north shore of Dead River Storage Basin (locality A, fig. 2). Arrow indicates north.

shortened parallel to the foliation, produced contractional kink bands with angle α approximately equal to angle β. Several field studies (for example, Kleist, 1972; Murphy, 1988; Stubley, 1989) have verified the similarity of angles α and β associated with constrictional kink bands. Extensional kink bands, in contrast, are characterized by a geometry in which angle β is much greater than angle α (Ramsay and Huber, 1987, p. 430).

Most kink bands of this study, however, do not exhibit a conjugate relationship. Kink bands take on either an S or a Z symmetry (fig. 13) depending upon the local rotational sense imposed on the rock anisotropy. For example, figure 12 shows monoclinic kink bands having only S symmetry. Throughout most of domains II and III only the steeply dipping, northwest-striking S-symmetry kink bands occur (fig. 14*A*, *B*). Most of the sparse Z-symmetry kink bands dip steeply and have easterly strikes.

The hinge lines of the kink bands plunge vertically (fig. 14*A*, *B*) and are parallel to both the intersection of conjugate kink planes (S and Z symmetry) and the hinge lines of the D_4 crenulations (fig. 11). This parallelism and the fact that both the kink bands and the crenulations formed as a result of similarly oriented layer-parallel compression suggest their concomitant development.

D_4 Strike-Slip Shearing

Rotated asymmetrical tension veins, consistent with both dextral and sinistral strike-slip displacement, indicate late-stage, brittle-ductile transcurrent shearing along both the Dead River and Carp River Falls shear zones.

A prominent shallowly to steeply plunging stretching lineation, which may have developed during the transcurrent shearing, occurs within both the type-b rhyolite and the type-a rhyolite of the sheared rhyolite tuff member of the Mona Schist. Sparse agglomeratic clasts within the type-b rhyolite are elongate in the shear foliation (C plane) and plunge shallowly. These lineations are deformed by both D_4 kink bands and D_4 crenulations. Stretching lineations within the type-a rhyolite are defined by elongate quartz phenocrysts, and have a highly variable plunge within the steeply dipping, easterly striking plane of the shear foliation (compare fig. 18*B*). Aggregates of white micas are aligned in the foliation and are locally deformed by well-developed D_4 crenulations.

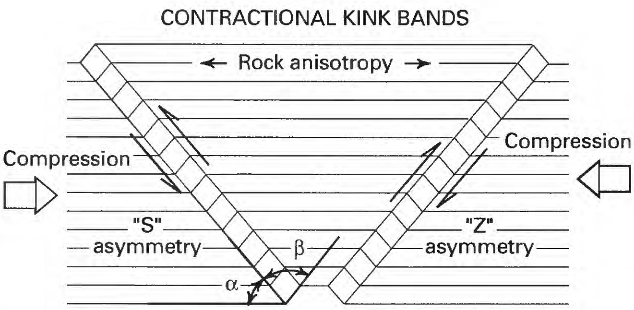


Figure 13. Schematic illustration of the geometry of conjugate kink bands formed by compression parallel to a preexisting planar rock fabric (modified from Ramsay, 1962). Note the angles α and β. Barbs show relative direction of kink formation.

Steeply plunging folds in the most intensely deformed parts of the shear zones (fig. 15) have vertical hinge lines that are parallel to the hinge lines of D_4 kink bands, but they are distinct from D_4 kink bands because they have curved hinge zones. These vertically plunging folds could not have formed as a result of the nearly vertical shear displacement associated with D_3 shearing. We suggest, however, that they may have formed in response to transcurrent shearing. The S-symmetry of the folds is consistent with folding of perturbed shear planes during the late stages of sinistral strike-slip shearing. (Compare Hudleston and others, 1988; Bauer and Bidwell, 1990.) The relationship of these folds to strike-slip shearing, however, cannot be unequivocally established.

Early Proterozoic Folding, Domain II

Recent workers (Klasner, 1972, 1978; Klasner and others, 1988) have suggested that the Early Proterozoic rocks of western Upper Michigan were subjected to at least three deformations. The first deformation formed gently plunging, upright folds with west-northwest-striking axial surfaces in response to north- to north-northeast-directed shortening (Klasner and others, 1988). (Note for example the westerly plunging synformal axial traces shown at locality E in fig. 2.) The second deformation, associated with uplift of Archean rocks during the waning stages of the Penokean orogeny, is largely responsible for the development of structures such as the Marquette trough (Klasner and others, 1988). The third deformation, also associated with the late-stage uplift of Archean basement blocks, produced sparse conjugate kink bands in slaty rocks such as the Michigamme Formation (Klasner, 1978). The kink bands dip vertically and strike close to N. 20° E. (S symmetry) and N. 50° W. (Z symmetry). However, kinks are quite rare and most commonly occur in Early Proterozoic rocks that crop out near the west end of the northern complex (fig. 1).

The Early Proterozoic deformation fabrics that we examined in the Negaunee area are consistent with the regional

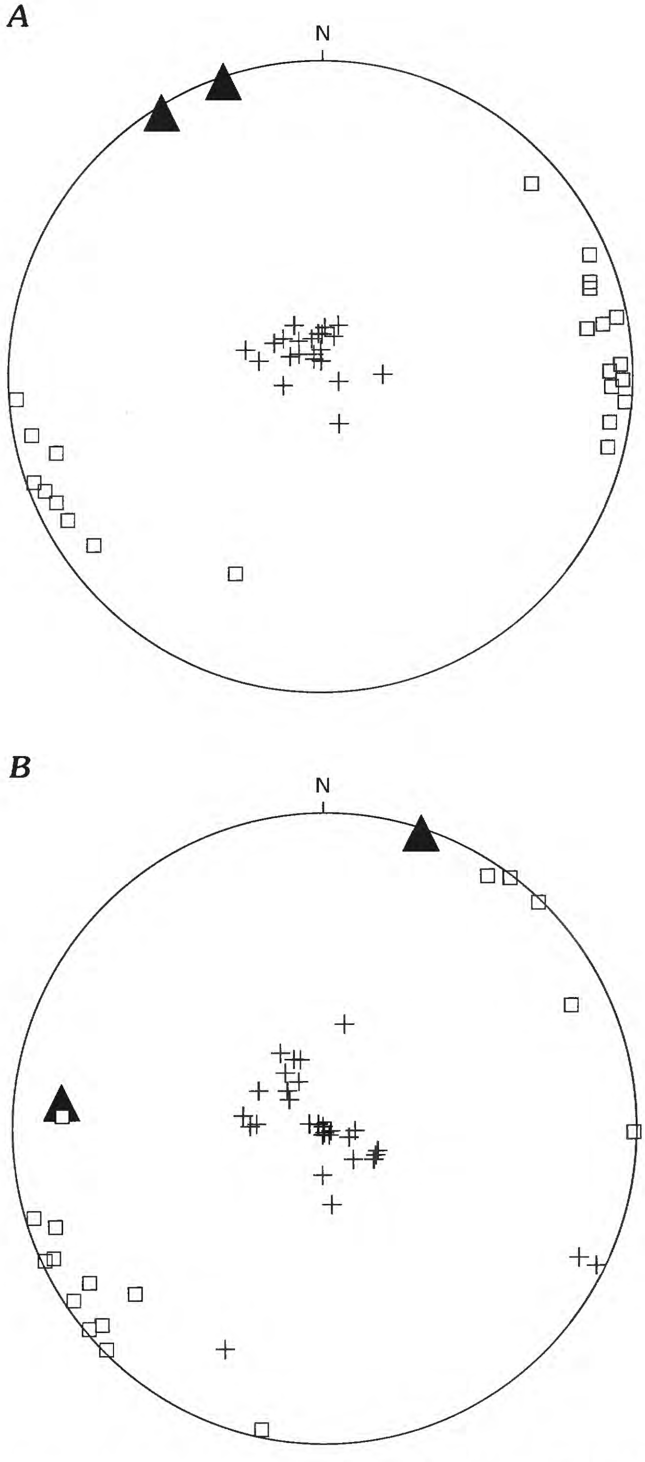


Figure 14. Equal-area projection of poles to (D_4) kink planes of S symmetry (square) and Z symmetry (triangle), and the plunge of (D_4) kink hinges (cross) from *A*, domain II; *B*, domain III.

orientation of Early Proterozoic fold axial planes associated with the first two Early Proterozoic deformations described by Klasner (1972, 1978) and Klasner and others (1988). We analyzed the geometry of folded Early Proterozoic Goodrich

Figure 15. Steeply plunging, asymmetrical fold in a D_3 shear zone along north shore of south lobe of Deer Lake (domain I). This shear zone was locally reactivated during D_4 strike-slip shearing; the fold is interpreted to have formed as a result of sinistral strike-slip shearing during D_4 deformation. Arrow indicates north.

Quartzite exposed in the west end of domain II (locality E, fig. 2), and used it as a local standard for Early Proterozoic deformation. Structural elements measured include bedding, cleavage that is axial-planar to folds in the bedding, and a lineation formed by the intersection of bedding and the cleavage. Poles to bedding (fig. 16*A*) define a well-constrained great circle with a best-fit Pi-axis plunging 23° to N. 69° W. The axial plane of the syncline dips steeply and strikes N. 69° W., subparallel to the spaced axial-planar cleavage that strikes approximately N. 70° W. (fig. 16*A*). The intersection lineation is well developed on foliation surfaces of the slaty layers and clusters about the best-fit Pi-axis in figure 16*A*.

The eastern segment of the Goodrich Quartzite is adjacent to the Nealy Creek Member of the Mona Schist. However, the axial trace of the synform defined by bedding plane orientations in the Goodrich Quartzite does not extend into the adjacent Archean rocks.

Early Proterozoic Reactivation of Shear Zones

Well-exposed segments of the Carp River Falls shear zone (domain I) north of Teal Lake (locality C, fig. 2) indicate Early Proterozoic reactivation of Archean basement rock. The Early Proterozoic Ajibik Quartzite contains a well-developed cataclastic fabric within the fault zone. Bedding of the quartzite in the fault zone is nearly vertical and strikes east, but bedding dips to the south at less than 60° just tens of meters south of the Carp River Falls shear zone. Vertical slickensides and vertical stretching lineations in the quartzite indicate that the last recognizable displacement on the fault was vertical. These observations and interpretations are consistent with those reported by Gair and Thaden (1968) in which well-exposed Archean rocks adjacent to Early Proterozoic rocks in the Marquette trough were displaced along a nearly vertical shear zone in a north-side-up relative sense.

Early Proterozoic brittle deformation in the Archean rocks in the fault zone is defined by veins that contain quartz and associated hydrothermal minerals. The vein assemblage in both the Late Archean Kitchi Schist and the Early Proterozoic Ajibik Quartzite across the fault zone includes quartz ± carbonate minerals ± galena ± chalcopyrite ± pyrite. R.C. Johnson (written commun., 1989) suggested that this assemblage is a common base-metal mineralization product precipitated from Early Proterozoic hydrothermal fluids.

In domain III (fig. 3), the structural juxtaposition of the Archean rocks to the north of the Early Proterozoic rocks also implies north-side-up, dip-slip relative displacement associated with Early Proterozoic reactivation of the Dead River shear zone. We did not, however, attempt to better define this younger brittle deformation, due to poor exposures.

FINITE STRAIN ANALYSIS

Introduction

Analyses of finite strains in the rocks of the Negaunee area were completed recently by Carter and Palmquist (1986) and Carter (1989) in Archean rocks, and by Westjohn (1978, 1986, 1987), Meyers (1983), and Carter (1989) in Early Proterozoic rocks (fig. 16*B*). These studies were conducted to examine how the finite strains are related to the deformation fabrics developed in these rocks. The finite strain analyses completed for our study were obtained to (1) extend the work of Carter (1989), who attempted to distinguish Early Proterozoic and Archean finite strains in rocks of the southern Ishpeming greenstone belt, (2) assess the extent to which shear strains modified finite strain in the felsic Archean rocks in southern parts of the Ishpeming greenstone belt, and (3) determine the nature of finite strains imposed on type-a and type-b rhyolites in the Dead River shear zone. The results of our analysis indicate that (1) the

XY principal plane of finite strain is subparallel to the S_2 foliation, and nearly vertical extension occurred during the development of S_2 foliation; (2) finite strains determined for samples of the Kitchi Schist, which has obvious D_3 shear indicators, are indistinguishable from finite strains determined for samples that do not have obvious D_3 shear indicators; and (3) the orientations of the principal planes of the finite strain ellipsoid in the type-a and type-b rhyolites of the sheared rhyolite tuff member of the Mona Schist are significantly different from those in other parts of the Ishpeming greenstone belt. These different orientations reflect complex deformation within the Dead River shear zone.

Two-dimensional finite strain analyses were obtained using the R_f/ϕ technique, which has been widely used to determine strains from ellipsoidal particles with initially random orientations (Ramsay, 1967; Dunnett, 1969; Siddans and others, 1984). We obtained two-dimensional strain ellipse data from oriented hand samples, from photographs of flat outcrop surfaces, and from direct ellipticity measurements on flat outcrop faces containing deformed lapilli, agglomeratic clasts, or quartz phenocrysts. To maximize the accuracy of the analysis, the outcrop faces and slab cuts used in the analysis were near the orientation of the principal planes of the finite strain ellipsoid estimated from the rock fabrics. To evaluate the possibility of initial primary orientation of the clasts, we used the Isym technique of Lisle (1985). We concluded that the R_f/ϕ method was applicable to these rocks because 90 percent of the two-dimensional finite strain analyses met the Isym criteria for a 90-percent confidence interval (Nachatilo, 1991).

We applied Owens' (1984) technique to determine the best-fit finite strain ellipsoid from the two-dimensional finite strain ellipses obtained from three nonorthogonal planes. Because we used two-dimensional finite strain data for three independent planes in each analysis, the solution to the symmetrical strain tenor is overdetermined. Owens (1984) used this overdetermined condition to develop a criterion for goodness of fit to an ellipsoid. In all cases, our calculated ellipsoid shape fell within the acceptable criteria suggested by Owens (1984).

Kitchi Schist and Lower Member of the Mona Schist

Finite strain analyses were performed on agglomeratic clasts of the Kitchi Schist because they are similar in composition to their matrix, indicating a low competency contrast between the clasts and the surrounding matrix. A low clast-matrix competency contrast should produce relatively homogeneous clast-matrix deformation, so that the strain sustained by the clasts is equivalent to the bulk strain. However, petrographic observations showed that fabric development is stronger in the matrix, and that strain shadows developed parallel to the maximum principal axis of

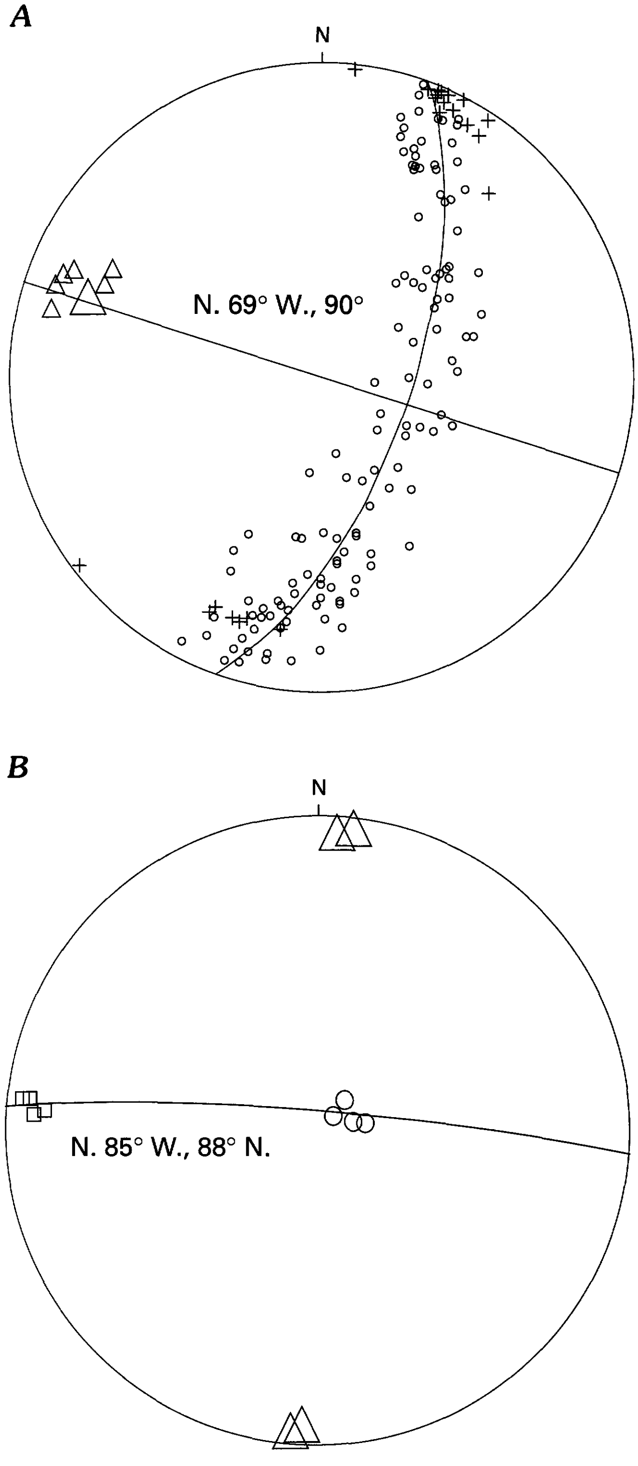


Figure 16. Equal-area projection of Early Proterozoic fabrics and finite strain axes of the Negaunee area. *A*, Structures associated with the folded Goodrich Quartzite in domain II (fig. 2, locality E). Poles to bedding (open circle), poles to axial plane foliation (cross), bedding-foliation intersection lineations (small triangle), and π axis (large triangle) of the best-fit great circle (solid line) of poles to bedding. *B*, Orientation of principal axes (X, square; Y, open circle; Z, triangle) of finite strain in slate from the Early Proterozoic Kona Dolomite in the Marquette trough (data of Westjohn, 1978). The great circle shown is the best-fit XY principal plane of finite strain.

elongation (X) on the margins of the clasts. The strain analyses based on clast shape therefore record the minimum finite bulk strain.

We analyzed two types of agglomeratic samples—one group containing obvious shear features associated with D_3 north-side-up shear (type 1) and a second group lacking indication of shear (type 2). We believe that agglomerates subjected to the largest shear strains were tectonically disrupted and are not recognizable.

Figure 17*A* shows the orientation of the principal axes of finite strain in both agglomerate of the Kitchi Schist (localities 1–8, fig. 3) and metabasalt of the lower member of the Mona Schist. The principal axes of the finite strain ellipsoid are not significantly different for type 1 and type 2 samples; the principal axes of finite elongation (X, Y, and Z) are nearly vertical, east trending, and north trending, respectively. The orientation of the Y principal plane of finite strain is subparallel to the S_2 foliation (compare fig. 4*A*). The relative dimensions of the principal axes of the finite strain ellipsoid of the Kitchi Schist agglomerate, depicted on a logarithmic Flinn diagram, indicate moderately constrictional strains (fig. 17*B*). The relative dimensions of the principal axes of type 1 and type 2 samples are similar.

Finite strains from the metabasalt of the lower member of the Mona Schist (Carter, 1989) are similar to those determined from the Kitchi Schist agglomerate. (See fig. 17*A*, *B*.) Carter (1989) used deformed varioles within pillow basalts as strain markers ($R_f/ø$ technique) for his finite strain analyses. The orientations of the principal axes of finite strain are indistinguishable from the orientations of the principal axes of finite strain of the Kitchi Schist agglomerate, but the relative dimensions of the principal axes of finite strain (logarithmic Flinn diagram, fig. 17*B*) indicate that the magnitude of finite strain evident on the Kitchi Schist agglomerate is somewhat greater than and more constrictional than that evident in the lower member of the Mona Schist. A recent study of quartz strain shadows on hematite porphyroclasts in a chlorite schist within the lower member of the Mona Schist indicates almost 100 percent nearly vertical elongation (Palmquist, 1990), consistent with our estimates of finite strain.

Sheared Rhyolite Tuff Member of the Mona Schist

Two types of samples containing finite strain markers appropriate for the $R_f/ø$ technique were chosen for finite strain analysis. The first type (type-a) contains deformed quartz phenocrysts from the type-a rhyolite (localities 10, 12, and 13, fig. 3). The second type (type-b) contains matrix-like clasts from the agglomeratic parts of the type-b rhyolite (localities 9 and 11, fig. 3). The specimens were carefully chosen so that the phenocrysts were not kinked or crenulated.

Quartz phenocrysts were used as strain markers in the type-a rhyolite samples. These markers were significantly more competent than their matrix; accordingly, they record a relatively smaller proportion of the bulk finite strain sustained by the samples. The least principal axis of finite elongation (Z) trends northeast and plunges shallowly. The XY principal plane of finite strain is nearly vertical and strikes east-northeast (open symbols in fig. 18*A*). The orientations of the long (X) axes of finite elongation vary from shallowly to moderately plunging in the XY plane and are consistent with the variable orientation of stretching lineations in this unit (fig. 18*B*). The relative dimensions of finite strain indicate both apparent constrictional and apparent flattening strains (fig. 18*C*).

Type-b rhyolite samples contain clasts that are similar in composition to the matrix and thus record a larger proportion of the finite bulk strain sustained than the type-a rhyolite. The orientation of the minimum axis of finite elongation (Z) plunges shallowly to the south-southwest and the XY plane is nearly vertical and strikes west-northwest.

Early Proterozoic Metasedimentary Rocks

Finite strain in Early Proterozoic rocks of the area was not measured during this study. However, previous studies of Carter (1989), Westjohn (1987, 1986, 1978), and Meyers (1983) provide representative finite-strain data for the Early Proterozoic rocks. The principal axes of finite elongation ($R_f/ø$ technique) determined from reduction spots in slate in the Early Proterozoic Kona Dolomite from the Marquette trough (Westjohn, 1978) are shown in figure 16*B*. The maximum principal axis of finite strain (X) is nearly vertical, the intermediate principal axis of elongation is east-trending, and the minimum principal axis of elongation is north-trending. The XY plane of finite strain is consistent with the steeply dipping, east-striking rock cleavage we observed in the area of our reference Proterozoic fold (locality E, figure 2; compare fig. 16*A*). The associated ellipsoid shape data, shown on the logarithmic Flinn diagram (fig. 18*C*), indicate apparent flattening.

KINEMATIC FRAMEWORK OF THE DEFORMATIONS

Focus of Discussion and Results

In our study we became convinced that the probable orientation of the regional stresses and related finite strain axes that developed during orogenesis are related to fabric elements in the study area. As an aid to interpreting the finite strain data and considering the implications for Archean orogenesis in the Ishpeming greenstone belt, we have outlined the kinematic framework of each deformation, including a mechanical interpretation of each separate deformation. This analysis indicates that the principal axis of stress (σ_1) was reoriented during Archean orogenesis. σ_1 was subhorizontal and roughly north to north northeast trending during D_2; moderately plunging and north trending during D_3; and subhorizontal and east to northeast trending during D_4. This change in the kinematic framework is lacking in the Early Proterozoic rocks of the region, which nevertheless contain fabric elements similar to those generated during the Archean D_2 deformation. From this we conclude that deformation features and finite strains in the Proterozoic rocks postdate the D_4 deformation in the Archean rocks and that the Archean rocks were subjected to little or no ductile Early Proterozoic deformation.

Archean Deformations

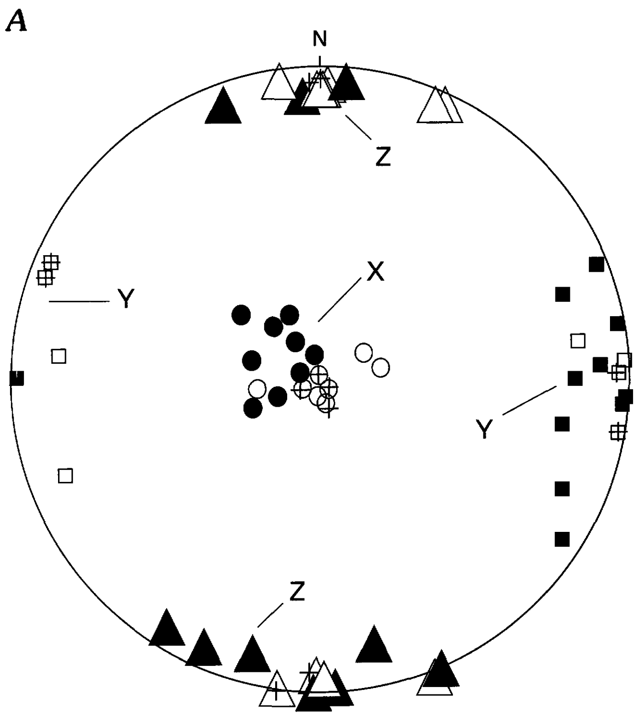
D_2 Deformation

The relationships among fabric orientation, the orientation of the principal axes of finite strain (X, Y, and Z), and the instantaneous principal stress axes (σ_1, σ_2, and σ_3) during progressive deformation have been addressed by numerous workers (for example, Wood, 1974; Williams, 1978; Gray and Durney, 1979). These studies indicate that foliation normally develops parallel to the XY principal plane of the finite strain ellipsoid. Although crenulation cleavages may be initiated within the plane of maximum shear stress in rocks containing a strong preexisting deformation fabric (Tewksbury, 1986; Hobbs and others, 1976; Cosgrove, 1976), this relationship is uncommon (Tewksbury, 1986), and clearly does not provide an appropriate model for the development of S_2 foliation considered here.

The regional orientation of the S_2 foliation in the study area is steeply dipping and west northwest striking (fig. 4*A–C*). S_2 foliation is nearly parallel to the XY plane of the finite strain ellipsoid defined by finite strains attributed to D_2 (fig. 17*A*) and is consistent with north- to north-north-east-directed subhorizontal coaxial shortening (Nachatilo and Bauer, 1990). The strain analyses further indicate that the maximum principal axis of elongation (X) was nearly vertical during D_2 deformation. The orientation of D_2 deformation fabrics in the study area is consistent with those in other areas of the Ishpeming greenstone belt. (See Johnson and Bornhorst, 1991; Clark and others, 1975; Puffett, 1974.)

D_3 Deformation

Brittle-ductile D_3 shearing is localized within the Dead River and the Carp River Falls shear zones as well as along the contact between the Dead River pluton and the Nealy Creek Member of the Mona Schist. D_3 shear features, including en-echelon tension veins (fig. 8), S–C mylonitic fabrics, and asymmetrical strain shadows (fig. 9), indicate localized noncoaxial deformation leading to nearly vertical, north-side-up relative displacement on east-striking shear



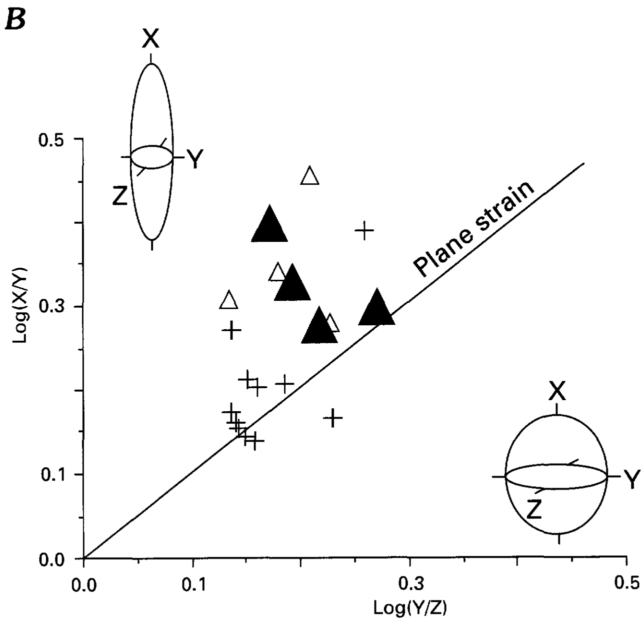


Figure 17. Finite strain data (X, Y, and Z) from rocks of the southern Ishpeming greenstone belt (domain I). *A*, Equal-area projection of the orientation of principal axes of finite strain in felsic agglomerate of the Kitchi Schist (open symbols, this study) and metabasalt of the lower member of the Mona Schist (solid symbols, data of Carter, 1989). Data points from samples of the agglomerate that contain obvious shear fabrics (type 1) include a cross in the open symbol; open symbols without a cross are data points representing samples with no indication of shear (type 2). *B*, Log Flinn diagram of finite strain from agglomerate of the Kitchi Schist (triangles, this study) and metabasalt of the lower member of the Mona Schist (crosses, data of Carter, 1989). Solid triangle, type-a rhyolite with obvious shear fabrics; open triangle, type-b rhyolite lacking shear fabrics.

zones (fig. 7*A*, *B*). In contrast to the D_2 deformation, the kinematic framework of D_3 features developed in response to a steeply to moderately north plunging maximum principal stress.

The geometry and kinematic framework of shearing deduced by Johnson (1990) in other parts of the Ishpeming greenstone belt are consistent with the results from this study, but the interpretation of the origin of the shearing differs. Johnson (1990) reported a shear zone in the Lighthouse Point Member of the Mona Schist north of the DRSZ that dips steeply to the north and is consistent with north-side-up relative displacement. The shear zone cuts across the flat-lying structural grain of bedding and S_1 foliation. Johnson interpreted the shear zone to be caused by north- to north-northeast-directed shortening that accompanied D_1 and D_2 deformations.

Two possible scenarios could explain the orientation and relative displacement on the D_3 shear zones. In the first model, consistent with Johnson's interpretation, the shear zones were initiated at relatively low angles while the greenstone belt was being horizontally shortened (D_2), and the shear zones were progressively rotated to nearly vertical orientations. In the second model, the shear zones were initiated at their current nearly vertical orientations in a kinematic framework in which the maximum principal stress axis (σ_1) was more steeply dipping than that envisioned for the D_2 deformation.

The first model requires the accumulation of large shear strains during progressive rotation of fault planes from typical low-angle reverse faults (approximately 20°–40°) to nearly vertical orientations. Our strain data from the Kitchi Schist, which are clearly distinct in orientation and magnitude from the D_2 strains (figs. 17, 18), do not indicate that such large shear strains exist in D_3 shear zones. We are not certain that our strain data from samples containing D_3 shear indicators necessarily reflect the full magnitude of D_2 strains that may have been concentrated within the shear zones. Nevertheless, we think it unlikely that the contact between the Dead River pluton and the metavolcanic rock of domain II, which displays locally well developed D_3 shear (fig. 10),

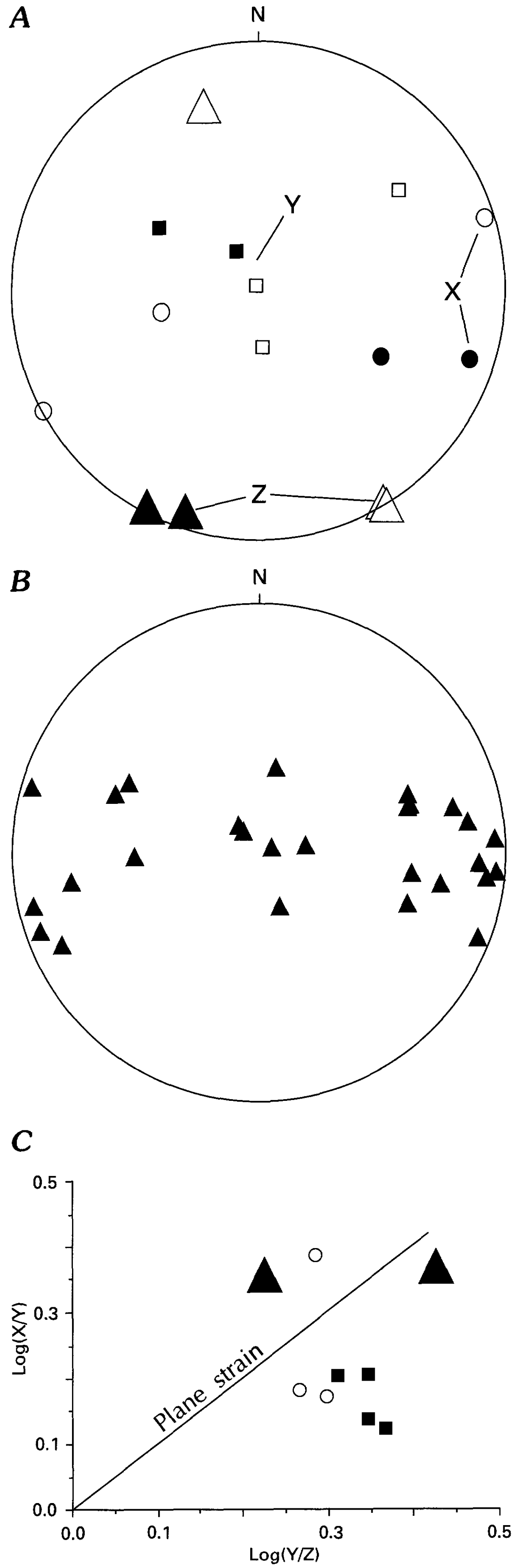


Figure 18 (facing column). Finite strain data from rocks of the sheared rhyolite tuff member of the Mona Schist. *A*, Equal-area projection of the orientation of principal axes of finite strain (X, Y, and Z) from samples in domain III. Three of the samples are type-a rhyolite that contain deformed quartz phenocrysts (open symbols) and two samples are type-b rhyolite that contain matrix-like clasts (solid symbols). X, dots/circles; Y, squares; Z, triangles. *B*, Equal-area projection of the orientation of D_4 stretching lineations from the type-a rhyolite (domain III) defined by elongate quartz phenocrysts. *C*, Log Flinn diagram of finite strains from the sheared rhyolite tuff member (domain III) and slate of the Early Proterozoic Kona Dolomite (solid squares, data of Westjohn, 1978). The data from the present study include analyses from type-a rhyolite (open circles) and type-b rhyolite (solid triangles).

could have originated as a shallow southerly dipping shear zone that was rotated to its current vertical orientation.

We believe the mechanical constraints imposed by our observations adjacent to the Dead River pluton and our finite strain data to be more consistent with the second model for the development of D_3 shear zones, in which the shear zones developed after D_2 deformation during which steep fabrics in the rock sequences were developed. This model requires a steepening of the greatest principal stress in the vicinity of the shear zones in order to effect the north-side-up displacement. We cannot, however, eliminate a link between the D_3 shearing and progressive D_2 deformation. The shear zones may have become localized during the progressive steepening of the east-trending rock units during D_2. This could explain the consistency of the principal axes of strain between rocks affected only by D_2 and those containing both D_2 and D_3 features. Our data do not definitely resolve this relationship.

D_4 Deformation

D_4 deformation is characterized by the common development of D_4 crenulations and by a more restricted development of crenulation cleavages, kink bands (fig. 12), and strike-slip shear features. D_4 structures are best developed along D_3 shear zones and within Archean rocks that contain a strong S_2 foliation. Well-developed D_4 crenulations are generally asymmetrical, and D_4 contractional kink bands have monoclinic symmetry and do not commonly occur in conjugate sets. D_4 strike-slip brittle-ductile shearing promoted the development of en-echelon tension veins.

Relationship of D_4 Features to Shear Zones

We have discussed the small-scale buckles associated with D_4, assuming that they are microbuckles developed through foliation-subparallel shortening. However, recent workers (for example, Platt and Vissers, 1980; Platt, 1983, 1984; Dennis and Secor, 1987, 1990; Hudleston and others, 1988; Bauer and Bidwell, 1990; Williams and Price, 1990) have shown that buckling phenomena may occur in response to continued noncoaxial strains in developing shear zones. In such cases, C foliations developed within the shear zone may undergo buckling in response to local perturbations in the finite strain field during continued shear. Figure 15 shows a steeply plunging fold that may have developed by this mechanism during the D_4 strike-slip shearing.

Williams and Price (1990) conducted shear deformation experiments on initially foliated rock and showed that kink bands with conjugate geometries can be developed in shear zones where the boundaries of the shear zone are inclined to the preexisting foliation. Although D_4 kink bands are found within shear zones in the study area, we interpret the development of these structures as a result of layer-subparallel shortening, in contrast to rotational deformation during progressive shear. Two observations lead to this conclusion. First, kink bands and crenulations with locally developed crenulation cleavages occur within rocks that do not appear to be sheared and that are in areas far from the Dead River and the Carp River Falls shear zones. For example, they are observed in domain II more than 5 km outside the region mapped as the Dead River shear zone. The D_4 crenulation hinge lines (fig. 11), parallel to the vertical hinge zones of kink bands (fig. 14*A*, *B*), are a well-developed fabric element in the study areas. Fabric development within the boundaries of a shear zone, in contrast, is much more localized (Ramsay, 1980). Although D_4 crenulations occur extensively in the shear zones, such mechanical behavior is predicted for rocks containing a strong preexisting fabric, that are shortened subparallel to the rock anisotropy (Paterson and Weiss, 1966; Cobbold and others, 1971; Cosgrove, 1976).

Also, the morphology of the kink bands (fig. 12) is inconsistent with crenulations having developed during progressive shear (Dennis and Secor, 1987, 1990). The angular relationship of the kink planes with respect to the foliation planes of the kink bands is consistent with those produced in experimental compressional deformation of foliated rocks (Donath, 1969; Anderson, 1974); that is, angle α is approximately equal to angle β (fig. 13).

Although we interpret the development of D_4 folds outside shear zones to be a result of buckling instabilities due to layer-subparallel shortening, some of the folding that occurs locally within the shear zones may have developed in response to progressive shear. For example, asymmetrical folds, like the fold shown in figure 15, occur in strongly sheared rock in domain I and may have resulted from sinistral, strike-slip shearing.

Stress Orientations and Kink Band Development

The orientation of kink band propagation bears a predictable relationship to the imposed stress field (Ramsay, 1962; Paterson and Weiss, 1966; Gay and Weiss, 1974; Weiss, 1980). In triaxial compression experiments where a material with a strong preexisting foliation is loaded with σ_1 parallel to the plane of the foliation, conjugate kink bands develop; σ_1 bisects the obtuse angle between the kinks and σ_2 is parallel to the intersection of the kink planes. In experiments where strongly foliated rocks are loaded with σ_1 slightly oblique to the plane of foliation, one set of kink bands tends to develop preferentially over the other (Donath, 1969; Cobbold and others, 1971; Gay and Weiss, 1974). On the basis of these experiments, several field studies have used the orientation of conjugate kinks to constrain the orientation of the principal stress axes associated with kink band development. (See for example Kleist, 1972; Tobish and Fiske, 1976; Tewksbury, 1986; Murphy, 1988; Babaie and Speed, 1990).

The D_4 kink bands observed in this study are more commonly of S symmetry than Z symmetry, indicating that the axis of maximum principal stress (σ_1) was inclined to the rock anisotropy. By assuming that σ_1 bisects the obtuse angle between sets of conjugate kink bands and noting that the obtuse angle between these conjugate kink bands averages 115°, σ_1 can be computed from the kink band data set (fig. 14*A*, *B*). Figure 19*A* shows the trend of σ_1 assuming that it was inclined 57.5° from the kink band within a horizontal plane. The results indicate that during D_4 the trend of σ_1 was west to northwest, σ_2 was nearly vertical, and σ_3 was north to northeast trending.

Experimental deformation studies of phyllites under moderate to high confining pressure indicate that the principal stress cannot be inclined more than approximately 30° to the rock anisotropy and still produce kink bands (Paterson and Weiss, 1966; Donath, 1968). Gay and Weiss (1974) suggested that if the rock anisotropy is inclined more than 5° to σ_1, a single set of kink bands (S or Z symmetry, see fig. 12) would develop in most cases. The results of these deformation experiments predict that S-symmetry kink bands would form more easily than the Z-symmetry kink bands in rocks of this study. If the orientation of the preexisting S_2 foliation was nearly vertical and striking approximately N. 70° W. (its present orientation), a northwest-directed compression would impose a preferential counterclockwise (S-symmetry kink) rotation on the foliation in this stress regime (fig. 19*B*). The calculated west- to northwest-directed compression is within the 30° limit (Paterson and Weiss, 1966; Donath, 1968) of σ_1 inclination from the rock anisotropy.

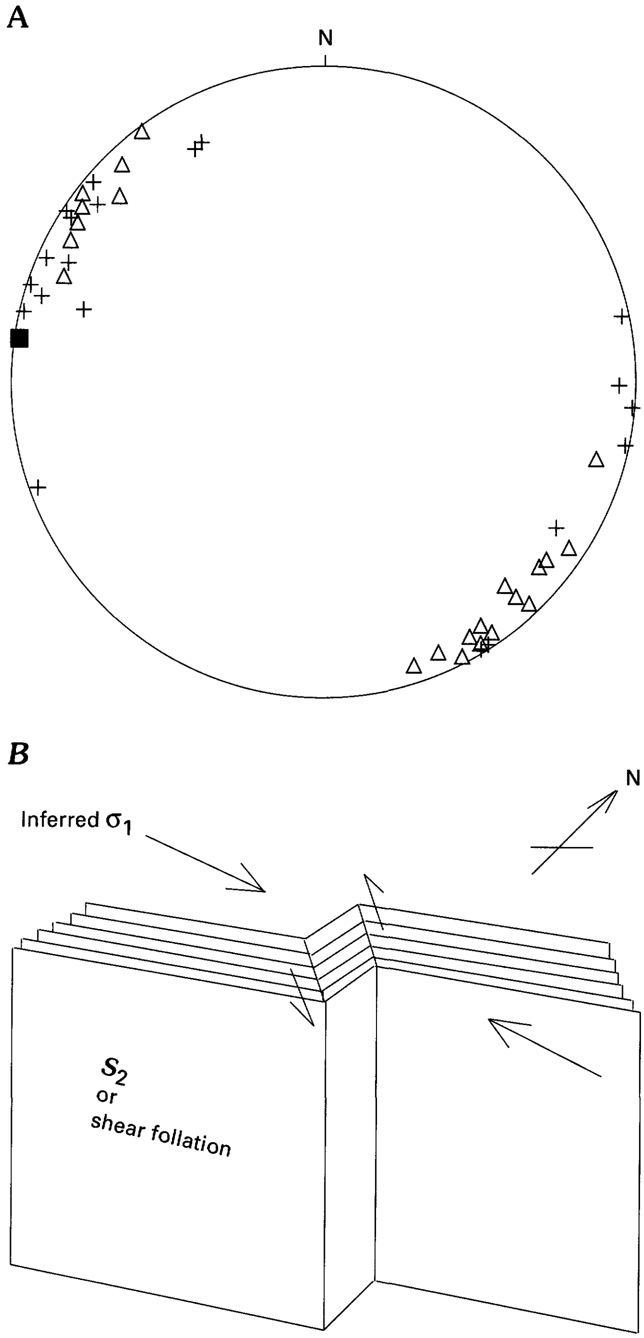


Figure 19. Principal stress orientations inferred from kink bands in Archean rocks. *A*, Equal-area projection of the calculated orientation of the maximum principal stress axis (σ_1) from kink band orientation data collected from domains I (solid square), II (triangle), and III (cross). Not shown are σ_2. which is nearly vertical, and σ_3, which is north to northeast trending. *B*, Schematic representation of the development of kink bands within the inferred D_4 stress regime (northwest-directed compression). Note that compression oblique to preexisting deformation fabric results in kink bands with primarily S symmetry. (See also fig. 13.)

Early Proterozoic Deformation

Klasner and others (1988) suggested that three periods of deformation affected Early Proterozoic metasedimentary rocks in Upper Michigan. The first two were coaxial (Klasner, 1972, 1978; Klasner and others, 1988; Klasner and others, 1991). The foliations associated with these deformations are nearly vertical and strike west-northwest (see Klasner, 1972, 1978), consistent with north- to north-northeast-directed shortening.

The second deformation was associated with late-stage block uplifts and reactivation of Archean faults. This deformation produced features such as the Marquette trough (fig. 2). Klasner (1978) suggested that this stage of deformation occurred within a kinematic framework defined by a steeply plunging maximum principal stress axis. The relative displacement on dip-slip shear zones developed during this deformation was brittle and north-side-up.

The third deformation produced conjugate kink bands. However, the geometry of conjugate kink bands in Early Proterozoic rocks indicates compression at an inclination of less than 5° to preexisting foliation. Klasner (1978) reported that these rare, vertically dipping kink bands strike N. 20° E. (Z symmetry) and N. 50° W. (S symmetry). The bisector of the obtuse angle formed between these kink planes, approximating the orientation of the maximum principal stress axis (σ_1) that kinked the foliation, trended N. 75° E. The intermediate principal stress axis (σ_2), parallel to the intersection of the conjugate kink bands, was nearly vertical. The minimum principal stress axis (σ_3), bisecting the acute angle between conjugate kink bands, trended N. 15° W. Klasner and others (1991) described a north-northwest-striking Proterozoic S_3 foliation dipping moderately to the west that deforms a mylonitic foliation in Archean gneiss of the Plumbago Creek area along the west margin of the northern complex. This foliation may have formed under the same regional stress regime that produced the D_3 Early Proterozoic kink bands, but this foliation orientation is not observed in the Archean rocks of the Negaunee area.

Effects of Early Proterozoic Deformation on Archean Basement Rocks

The kinematic frameworks indicated by deformation features in Archean and Early Proterozoic rocks are similar; both north-side-up, dip-slip relative displacement and horizontally transmitted shortening subparallel to foliation are indicated by small-scale deformation features in Early Proterozoic and Archean rocks. However, certain notable differences exist between these Early Proterozoic and Archean deformation features. First, the orientation of σ_1 inferred from the geometry of contractional kink bands in Early Proterozoic metasedimentary rocks indicates a late-stage, horizontal compression oriented N. 75° E. However, the geometry of kink bands in the Archean rocks indicates a horizontal compression that is west to northwest trending (fig. 19*A*). Second, the occurrence of kink bands in Early Proterozoic rocks in Upper Michigan is not extensive; they are only reported in areas near the west end of the northern complex (Klasner, 1978). Early Proterozoic slate outcrops are common, containing well-developed rock cleavage that is subparallel to Archean S_2 foliation. That a late-stage, foliation-subparallel shortening during Early Proterozoic orogenesis could have produced D_3 and D_4 deformations features in the Archean rocks but not in the Early Proterozoic rocks is unlikely. For example, D_4 fabric elements, such as crenulations, occur extensively in the Archean rocks of the study areas but are not well developed in the Early Proterozoic rocks. Third, the D_3 shearing imposed on Archean rocks is brittle-ductile in nature, whereas shearing of Early Proterozoic rocks in the Marquette syncline is brittle. It is more likely that Early Proterozoic deformation is imposed on Archean rocks along reactivated fault zones in a brittle fashion. Finally, an Early Proterozoic syncline (locality E, fig. 2) that overlies Archean rocks in domain II contains locally developed rock cleavage that is axial-planar to folded phyllite and quartzite bedding (fig. 16*A*). These Early Proterozoic planar fabrics and the axial plane of the upright fold are subparallel to the S_2 foliation in adjacent Archean rocks (see fig. 4*B*). Despite this parallelism, the adjacent Archean rocks show no evidence of folding by this Early Proterozoic fold.

INTERPRETATION OF FINITE STRAIN DATA

Several mechanisms can reasonably be put forth to explain the finite strains in rocks of the southern (domain I) and central (domain III) parts of the Ishpeming greenstone belt based on the geometry of fabric data. Our data herein provide support for the kinematic framework outlined in the previous section.

Rocks of the Ishpeming greenstone belt may have accumulated increments of finite strain through a variety of deformation mechanisms that are summarized schematically in figure 20. These mechanisms include (1) shortening associated with early F_1 recumbent folding (not observed in the study area), (2) shortening associated with upright F_2 folding, (3) dip-slip shearing during D_3 deformation, (4) shortening subparallel to the S_2 and S_3 foliations that led to buckling of these preexisting deformation fabrics during D_4 deformation, (5) strike-slip shearing during D_4 deformation, and (6) shortening associated with a thick-skinned Penokean orogeny.

From the available finite strain data, we conclude that (1) finite strain imposed on the felsic metavolcanic rocks of domain III and the metabasalt of the lower member of the Mona Schist resulted primarily from D_2 deformation. Although some of the rocks from this domain show evidence of D_3 shearing, the strains measured in obviously sheared samples are not significantly different than those measured in apparently unsheared samples. (2) Finite strains imposed on the type-a rhyolite of the sheared rhyolite tuff member of the Mona Schist are strongly affected by strike-slip shearing associated with D_4 deformation.

Strains in Domain I

D_2 Fabrics and Finite Strains

The XY principal plane of finite strain in the Kitchi Schist in domain I (figs. 3 and 17*A*) strikes west-northwest and is parallel to the local S_2 foliation (fig. 4*A*). Furthermore, the X axis of principal elongation is parallel to steep linear elements in the schist. The orientation of principal axes of finite strain in the adjacent lower member of the Mona Schist (Carter, 1989) is indistinguishable from those of the Kitchi Schist (fig. 18*A*); however, the magnitude of strain and the degree of apparent constrictional strain are both higher in the Kitchi Schist. The differences in the relative ratios of the principal axes of finite strain between the agglomerate of the Kitchi Schist and the lower member of the Mona Schist could be explained by differential volume loss, problems in the application of the R_f/ϕ technique, or differential ductility of these rock units.

Carter (1989) suggested that volume loss did not affect the strain markers of the lower member of the Mona Schist metabasalt because the devitrified glass varioles are

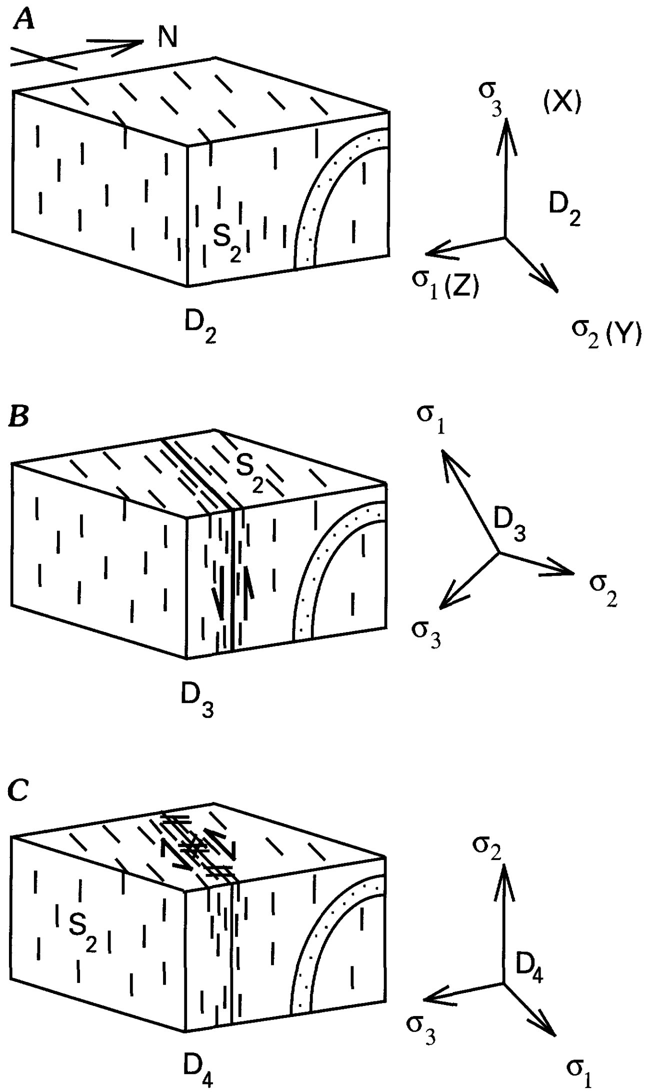


Figure 20. Schematic representation of the proposed Archean fabric geometries, kinematic framework of *A*, D_2; *B*, D_3; and *C*, D_4 deformations, and orientations of the principal axes of stress (σ_1, σ_2, and σ_3) (D_1 was not recognized in the study area). The principal axes of both elongation (X, Y, and Z) and principal stress are only constrained for D_2 deformation where the coincidence of stress and strain axes assumes progressive pure shear strain.

relatively immobile and therefore dissolution was negligible during greenschist-facies metamorphic conditions. Substantial volume loss within the clasts may also be ruled out for the Kitchi Schist because foliation resulting from pressure solution effects does not crosscut the clasts.

Problems with the finite strain analysis technique in all probability did not contribute significantly to errors in the analysis because the fabric data coincide with the principal axes of finite strain and the Isym test indicates no contribution of initial preferred orientation of the strain markers to the finite strain. Carter (1989) found that the R_f/ϕ technique was also effective in accurately defining the finite strain ellipsoid. For example, the XY principal plane of finite strain determined from the varioles is subparallel to the foliation, and symmetrical strain shadows on plagioclase porphyroclasts indicate near-vertical tectonic elongation. Carter also found no problem with a preexisting fabric orientation based on the Isym test.

Differences in the finite strains between the Kitchi Schist and the Mona Schist may, however, be explained by differences in their relative ductility and competence contrast during deformation (Nachatilo and Bauer, 1990). Ramsay (1983, p. 118) suggested that under greenschist-facies temperature and pressure conditions, metabasalt is one of the most competent rock units found within the crust. The Mona Schist may have been less responsive to the imposed strain than the Kitchi Schist. Furthermore, Freeman and Lisle (1987) have shown that clasts that are more competent than their matrix (such as the clasts used for the strain determination in the Kitchi Schist) show a more prolate strain than the bulk strain of the rock.

Effects of D_3 Shearing

Well-exposed parts of the Carp River Falls shear zone along the north shore of the southern lobe of Deer Lake (locality B, fig. 2) contain agglomeratic zones. The agglomerates that are spatially associated with well-developed shear zones contain clasts that show a well-defined nearly vertical preferred orientation. However, the finite strains of rocks that contain obvious shear fabrics (type 1) and those that lack shear fabrics (type 2) are indistinguishable (fig. 17*A*, *B*). Two possibilities can explain these similarities: (1) D_3 shearing did not significantly affect the finite strain accumulated by the clasts, and (2) D_3 shearing affected all the rocks but did not result in the preservation of kinematic indicators in all the rocks. Our data do not resolve these possibilities.

Two logistical problems hindered evaluation of these hypotheses. First, the boundaries of the shear zones are often difficult to delineate because S_2 and S_3 foliations are subparallel (figs. 4*A* and 7*A*) and outcrops are poor and discontinuous. Second, small and large finite strains are not represented in the analysis; this occurs because agglomerate clasts within zones of the highest shear strains were either absent or destroyed, and samples that did not demonstrate obvious tectonic strains were not analyzed.

Strains in Domain III

Recent work by Johnson (1990) indicates that the finite strains in rocks of the northern part of the Ishpeming greenstone belt have an east-trending maximum principal axis of elongation, whereas rocks of the southern Ishpeming greenstone belt display finite strains with a nearly vertical maximum principal axis of finite elongation.

Johnson (1990) suggested that shallowly plunging stretching lineations, defined by the alignment of amphiboles that occur in metabasalt units north of domain III, were caused by the superposition of F_2 upright folding on F_1 recumbent folds. This shallowly plunging elongation (X) is also indicated by shallowly plunging stretching lineations (fig. 18*B*) in both the quartz phenocrysts of the type-a rhyolite and agglomeratic clasts of the type-b rhyolite of the sheared rhyolite tuff member. However, these samples were collected in the vicinity of the Dead River shear zone and were subjected to substantial D_3 and D_4 deformation. In the following discussion of the type-a and type-b rhyolites, we compare the fabrics and finite strains recorded in these units with the regional fabric and strain orientations, and consider the probable D_3 and D_4 contribution to the finite strain in the rhyolites.

Type-a Rhyolite

The geometry of fabric and the finite strains developed in the type-a rhyolites differ substantially from those developed regionally in both Archean and Early Proterozoic rocks. For example, the planar fabrics and XY principal plane of finite strain in the type-a rhyolites are nearly vertical and strike east-northeast. This is in contrast to the nearly vertical west-northwest-striking plane of flattening, defined by S_2 foliation and the XY principal plane of finite strain, in Archean rocks of the Negaunee area (fig. 4*A–C*, fig. 17*A*). Furthermore, type-a rhyolite dikes crosscut the undifferentiated foliated pillowed basalt (MacClellan and Bornhorst, 1989) that contains upright F_2 folds (fig. 6), indicating that the dikes postdate most of the D_2 deformation.

The foliation in these dikes is deformed by D_4 crenulations and D_4 kink bands; therefore, the dikes must have intruded between the late stages of D_2 deformation and the early stages of D_4 deformation. Furthermore, the dikes lack shear fabrics that indicate north-side-up, dip-slip relative displacements, implying that they are not deformed by D_3. Johnson and Bornhorst (1991) suggested that these type-a rhyolite dikes, as well as those in other shear zones within the volcanic rocks of the Lighthouse Point Member, intrude areas of relatively high D_2 strain and that the fabrics developed in these dikes are primarily a result of post-D_2 shearing. D_3 deformation is highly localized, and although D_3 shear zones do not commonly occur in type-a rhyolite dikes, D_3 deformation is evident in the type-b rhyolite.

D_4 is expressed by two deformation mechanisms: coaxial finite shortening associated with buckling phenomena such as crenulations and kink bands, and noncoaxial shearing associated with such features as asymmetrical tension veins. The finite strains that deformed the quartz phenocrysts were imposed either by D_4 shear strains or by earlier deformation (late stages of D_2). For example, the long axis of finite elongation (X) of many quartz phenocrysts is at a relatively high angle to the axial plane of D_4 crenulations. Experiments by Paterson and Weiss (1966) show that little bulk shortening (about 5 percent) is required to promote the development of kink bands, but the finite strains indicate large finite shortening (about 45 percent, fig. 18*C*). Furthermore, because the matrix is less competent than the strain markers, the strains we obtained using the R_f/ϕ technique indicate the minimum bulk finite strain experienced by the rock.

Localization of finite strains associated with strike-slip shearing could explain the shallowly plunging maximum principal axes of elongation (X, fig. 18*A*) and shallowly plunging stretching lineations (fig. 18*B*). During progressive ductile shearing, the maximum principal axis of finite elongation within a shear zone is progressively rotated toward parallelism with the orientation of tectonic transport (Ramsay, 1980). This rotation would reorient finite strain markers toward the near-vertical and east-striking shear foliation (C planes) of the Dead River shear zone (fig. 7*B*). Three possible mechanisms thus exist to explain the finite strain data in the type-a rhyolite dikes: (1) D_4 strike-slip shearing, (2) a late-stage of D_2 shortening that was north to north-northwest directed, or (3) some combination of D_2 and D_4 strains.

Type-b Rhyolite

The finite strain indicated by the type-b rhyolite (fig. 18*A*, *C*) of the sheared rhyolite tuff member is more consistent with the fabrics developed in the northern part of the Ishpeming greenstone belt as reported by Johnson (1990) than with the type-a rhyolite dikes. However, these rocks are strongly sheared (Puffett, 1974), and that they share the same deformation history as the metabasalts north of the Dead River shear zone is unlikely. The XY principal plane of finite strain is nearly vertical and strikes west-northwest (fig. 18*A*), consistent with north- to north-northeast-directed shortening associated with D_2 deformation. The maximum principal axis of elongation (X, fig. 18*A*) indicates approximately N. 80° W.-trending elongation (fig. 18*B*). Rocks in the southern part of the Ishpeming greenstone belt, in contrast, indicate nearly vertical elongation (fig. 17*A*).

We believe that a significant component of D_4 deformation was partitioned into the type-b rhyolite relative to other rocks in the Ishpeming greenstone belt because these tuffaceous rocks were relatively less competent than the other Archean rocks. However, a detailed interpretation beyond this level of complexity is not feasible given the limited size of the data set, the complicated structural dynamics of the Dead River shear zone, and the difficulty in establishing the extent to which F_1 recumbent folding is developed in domain III.

IMPLICATIONS FOR ARCHEAN TECTONIC HISTORY

The dynamics of present-day mountain building processes are not well understood because rheological models of rocks in multilayered sequences are not yet adequate to predict large-scale tectonic interactions associated with orogenesis (Ramsay, 1983). Nevertheless, the end results of the dynamic interactions involved in mountain building processes are readily observed in many exhumed mountain belts, and are defined by small-scale deformation features. Models for the mechanical development of the small-scale structures described in this study, such as foliation, shear fabrics, crenulations, and kink bands, are well documented in the literature (Ramsay, 1967; Hobbs and others, 1976; Ramsay and Huber, 1983, 1987). Such models, coupled with the kinematic interpretation presented in this study, informed our attempt to set constraints on the tectonic evolution of the Ishpeming greenstone belt.

Dewey and Bird (1970) proposed several models of orogenesis that involve formation of mountain ranges at plate boundaries resulting from the convergence of oceanic crust, an island arc, or continental crust with another lithospheric plate. Their models are based on comparison with plate tectonic processes that are well established for the Phanerozoic. However, it is not certain that these plate tectonic processes are applicable to the Archean. Nevertheless, models that describe the mechanical behavior of an orogenic wedge impacted by a rigid indenter (Platt, 1986, among others) are applicable to any convergent orogenic setting. The mechanical development of the Ishpeming greenstone belt can be roughly extrapolated from current models of convergent tectonism regardless of the true nature of Archean plate interactions.

The reorientation of the principal stress axes during the Archean (fig. 20) seems to be well founded from the kinematic data. Prolonged Archean north- to north-northeast-directed shortening is supported by the geometry of folding and associated foliation and finite strains. However, late-stage deformation features, such as shear zones, crenulations with locally developed crenulation cleavages, and kink bands, indicate that reorientation of the regional stress field occurred during the late stages of Archean orogenesis.

Tobish and Fiske (1976) suggested that late-stage reorientation of the regional stress field is a common occurrence in many Precambrian (Naha and Halyburton, 1974) as well as Phanerozoic (Stubley, 1989) orogenic settings. They suggested the following model to explain late-stage reorientation of the stress field without changing the orientation of tectonic convergence: During progressive shortening in an orogenic wedge, rocks extend in the XY principal plane of finite strain. Vertical extension is accommodated by crustal thickening and formation of a stretching lineation, but the horizontal principal axis of finite elongation (Y), which is parallel to the margin of the fold belt, is constrained by space restrictions. Elastic strain is taken up in the Y direction, and as margin-normal compression wanes, "elastic recovery" occurs, inducing compression parallel to the preexisting deformation fabric.

Application of this genetic model, however, to the Ishpeming greenstone belt is problematic. Although finite strain and fabric data indicate near-vertical elongation, consistent with the Tobish and Fiske (1976) model, two arguments are in apparent opposition to the model. First, the Tobish and Fiske model predicts that "elastic recovery" will impose a compression that is nearly parallel to the preexisting foliation and produce kink bands with orthorhombic symmetry. Clearly the data indicate an asymmetric development of kink bands promoted by compression oblique to the preexisting foliation.

The second argument is that an intermittent deformation occurs between D_2 and D_4 with a different kinematic framework (fig. 20). D_3 north-side-up shearing is associated with a steeply inclined maximum principal stress axis. The existence of nearly vertical shear zones, which strike parallel to the structural grain of the belt, implies that shearing could not have occurred until the waning stages of orogenesis. For instance, Platt (1986) showed that extensional faulting at near-vertical orientations can occur if the stress field associated with convergence relaxes and nearly vertical gravitationally driven stresses locally exceed horizontally transmitted tectonic stress. However, it is unlikely that the rocks would retain the elastic strains required by the Tobish and Fiske (1976) model to induce compression parallel to the margin of the Ishpeming greenstone belt.

Recent models of deformation in the Superior province have emphasized convergent margin plate tectonic processes as a mechanism for the construction of the province (Card, 1990; Williams, 1990). These models call on northerly convergence resulting in early north-directed, south-side-down underthrusting along north-dipping shears followed by upright folding in a transpressive regime that culminated in widespread strike-slip shear (Hudleston and others, 1986; Hudleston and others, 1988; Williams, 1987; Percival and Williams, 1989; Bauer and Bidwell, 1990). General features of the deformation in the Negaunee area can be considered in the context of these models; however, the changes in kinematic framework during the progress of deformation in the Negaunee area are not entirely consistent with such models. It may be that the DRSZ and CRFSZ are early thrust-generated structures that have been repeatedly reactivated during the deformation sequence, but this idea is not supported by the finite strain data collected from the Carp River Falls shear zone (fig. 18). The early north-side-up dip-slip displacement in these zones is consistent with early dip-slip observed by Williams (1987) in volcanic sequences in the Beardmore-Geraldton area of Ontario; however, we interpret this displacement to postdate D_2 folding and fabric development. D_4 strike-slip shear could be consistent with late-stage strike-slip developed during the waning stages of regional transpression; however, kinematic indicators associated with strike-slip shearing indicate both dextral and sinistral relative displacements within the shear zones. As a result, we believe that further detailed investigations of the history of deformation in the shear zones of the region would be useful.

SUMMARY AND CONCLUSIONS

Four Archean deformations affected the rocks of the southern and central parts of the Ishpeming greenstone belt. D_1 deformation is confined to the northern part of the study area and is defined by a flat-lying foliation that is deformed by D_2 crenulations. D_2 deformation pervasively affects the entire Ishpeming greenstone belt, and is defined by a nearly vertical west-northwest-striking S_2 foliation that is axial-planar to upright F_2 folds and F_2 crenulations (domain III, fig. 3). D_3 deformation is defined by north-side-up dip-slip in narrow shear zones that are subparallel to the structural grain of the belt. D_4 deformation is defined by well-developed crenulations, kink bands with monoclinic symmetry, and strike-slip shear reactivation of D_3 shear zones.

Early Proterozoic Penokean deformation in Early Proterozoic metasedimentary rocks of the area also produced a nearly vertical, west-northwest-striking foliation that is axial-planar to upright Early Proterozoic folds. Although the Archean S_2 foliation and Early Proterozoic axial-plane orientations are subparallel, late-stage Archean deformations indicate a significant reorientation of the regional stress field. Inasmuch as these late-stage structures are absent in the Early Proterozoic rocks, we conclude that the Penokean orogeny did not significantly shorten the underlying Archean basement rocks in the Negaunee area.

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