Nature and Style of Deformation in the Foreland of the Early Proterozoic Penokean Orogen, Northern Michigan

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Chapter K

Nature and Style of Deformation in the Foreland of the Early Proterozoic Penokean Orogen, Northern Michigan

By J.S. KLASNER, R.W. OJAKANGAS, K.J. SCHULZ, and G.L. LABERGE

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CONTRIBUTIONS TO PRECAMBRIAN GEOLOGY OF LAKE SUPERIOR REGION

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

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By J.S. Klasner,[1] R.W. Ojakangas,[2] K.J. Schulz,[3] *and* G.L. LaBerge[4]

Abstract

Evidence for Early Proterozoic north-verging folding and thrusting in the continental foreland of the Penokean orogen is present in two widely separated areas in northern Michigan. In the eastern part of the exposed orogen, asymmetric to overturned folds in the Early Proterozoic Michigamme Formation suggest an initial (D_1) phase of possibly north verging thin-skinned deformation. A second phase (D_2) is characterized by a more thick skinned deformation consisting of northward thrusting of Archean gneiss and overlying Early Proterozoic quartzite along ductile thrust faults. Crosscutting shear zones indicate a third phase (D_3) of deformation involving east-northeast thrusting of Archean gneiss. Thick-skinned deformation D_2 and D_3 phases include spaced fracture cleavage, kink folds, and lineations in D_1 foliation surfaces.

Near the west end of the exposed orogen in Michigan, bedding-cleavage relationships in the Early Proterozoic Tyler Formation also indicate northward tectonic transport. These structures, which are interpreted as D_1, lie along the north edge of the Archean Puritan batholith and associated Archean greenstone.

The north-verging structures in the northern Michigan segment of the Penokean orogen were formed approximately 1,850 Ma during collision of the Wisconsin magmatic terranes with the continental foreland of Michigan, Wisconsin, and Minnesota.

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[1]Department of Geology, Western Illinois University, and U.S. Geological Survey, Macomb, IL 61455.

[2]Department of Geology, University of Minnesota-Duluth, and U.S. Geological Survey, Duluth, MN 55812.

[3]U.S. Geological Survey, Reston, VA 22092.

[4]Department of Geology, University of Wisconsin-Oshkosh, and U.S. Geological Survey, Oshkosh, WI 54901.

INTRODUCTION

The Early Proterozoic Penokean orogen is a major tectonic feature of the Lake Superior region (fig. 1). The northern (foreland) part of the orogen, in northern Michigan, Wisconsin, and Minnesota, which comprises the area of this report, consists of a continental margin assemblage of Early Proterozoic sedimentary and volcanic rocks overlying an Archean basement (Morey and others, 1982). This domain is flanked on the south by rocks of the Wisconsin magmatic terranes (Sims and others, 1989), and is separated from them by the Niagara fault zone, a major terrane boundary. Several authors (Van Schmus, 1976; Cambray, 1978; Larue and Sloss, 1980; Greenberg and Brown, 1983; Anderson and Black, 1983; Schulz, 1983, 1984; Schulz and others, 1984; LaBerge and others, 1984; Sims and Peterman, 1984; Holst, 1982, 1984; Holm and others, 1988; Klasner and others, 1985; Sims, Peterman, and Schulz, 1985; Klasner and Attoh, 1986; Schulz, 1987a, b; Sims, Peterman, and others, 1987; Sims, Van Schmus, and others, 1989; and Attoh and Klasner, 1989) have proposed plate-tectonic scenarios for the tectonic evolution of the Penokean orogen in the Lake Superior region. Although the scenarios differ in detail, these authors have suggested that evolution of the orogen began with a rifting phase accompanied by formation of basins and troughs (such as the Marquette and Republic troughs), which led to the development of a passive margin along the south edge of the Archean Superior craton. Subsequently, the arc-related volcanic and plutonic rocks were accreted to the Archean continental margin (Sims and others, 1989), resulting in northward thrusting of the continental margin rocks (Klasner, Ojakangas, and others, 1988; Klasner, Sims, and others, 1988; Attoh and Klasner, 1989) and at least local development of nappes (Holst, 1984).

Evidence for north-verging folding and thrusting exists in two areas in the foreland of the Penokean orogen in northern Michigan and Wisconsin that are separated by a

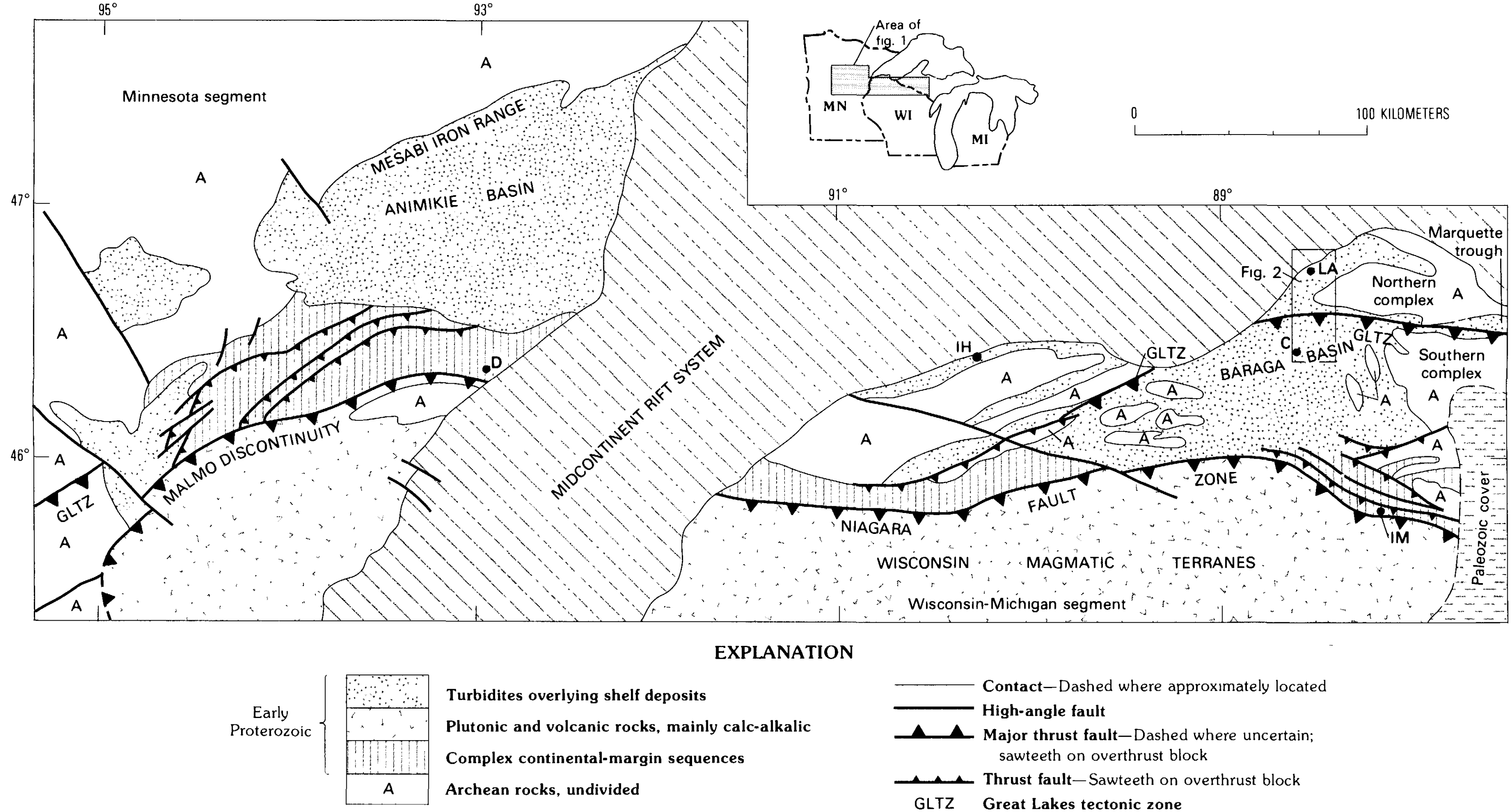

Figure 1. Map of northern Michigan, northern Wisconsin, and northern Minnesota segments of Penokean orogen, divided by rocks of Midcontinent rift system (modified from Southwick and Morey, 1991, fig. 1, and Sims and others, 1989). Towns mentioned in text are L'Anse, Mich. (LA); Covington, Mich. (C); Iron Mountain, Mich. (IM); Ironwood, Mich.–Hurley, Wis. (IH); and Duluth, Minn. (D). GLTZ, Great Lakes tectonic zone, from Morey and Sims (1976) in Minnesota, and Sims and others (1980) in Wisconsin and Michigan. Note location of figure 2 and Hurley, Wis. area.

Table 1. Generalized stratigraphic column from the eastern and western parts of Penokean orogen, northern Michigan

[The Paint River Group, which possibly lies stratigraphically above the Baraga Group in the Marquette Range Supergroup, is not shown. Modified from Cannon and Gair (1970) and James (1958)]

	West	East
EARLY PROTEROZOIC		
Marquette Range Supergroup (part)	**Michigamme, Copps, and Tyler Formations** Metagraywacke, argillite, and siltstone	**Michigamme Formation** Metagraywacke, slate, thin-bedded cherty iron-formation, mafic to intermediate volcanic rocks
Baraga Group		**Goodrich Quartzite** Conglomeratic quartzite
	Ironwood Iron-formation Cherty sideritic iron-formation	**Negaunee Iron-formation** Cherty-banded iron-formation
Menominee Group	**Emperor Volcanic Complex** Metabasalt	**Siamo Slate** Argillite and siltstone
	Palms Formation Argillite, quartzitic siltstone, quartzite	**Ajibik Quartzite**
Chocolay Group	**Bad River Dolomite** **Sunday Quartzite**	**Wewe Slate** **Kona Dolomite** **Mesnard Quartzite**
ARCHEAN	Undifferentiated granitic to mafic gneisses, metavolcanic rocks, granite	

distance of more than 150 km. The eastern area is near L'Anse, Mich., and consists of the Falls River, Little Mountain, Taylor mine, Plumbago Creek, Canyon Falls, Covington profile, and the Komtie Lake areas (fig. 2). The western area is near Ironwood, Mich., and Hurley, Wis. (fig. 1). Although evidence for north-verging folding and thrusting in northern Michigan has been discussed (for example, Klasner, Ojakangas, and others, 1988; Klasner, Sims, and others, 1988), it has not previously been fully documented.

Two distinct structural domains have been recognized in the continental margin rocks of northern Michigan. Klasner, Sims, and others (1988) and Klasner and Cannon (1989) suggested that the Penokean orogen of Michigan can be divided into (1) an imbricate thrust belt in the south and (2) a foreland thrust belt in the north. In the imbricate thrust belt, which is part of a broader marginal basement arch, deformation was thick skinned and complex—involving both Archean basement and Early Proterozoic supracrustal rocks. In the foreland thrust belt, structures are less complex and deformation was largely thin skinned, that is, mainly involving Early Proterozoic supracrustal rocks.

In this report we examine the structural evidence for folding and thrusting in the foreland thrust belt of the Penokean orogen in northern Michigan. A similar study by Klasner and P.K. Sims is being carried out in the Felch and Calumet troughs region to the south, within the imbricate part of the thrust belt in northern Michigan. We conclude this report with a brief discussion of the tectonic significance of the foreland part of the Penokean orogen.

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This paper benefited from critical reviews by W.F. Cannon and T.B. Holst. Connie Fairchild assisted with typing. Drill core data at Komtie Lake are from Resource Exploration; drill core at Taylor mine is from Ford Motor Company. Permission to examine the drill core at Komtie Lake was given by W. Bodwell of Resource Exploration. The drill hole data at Taylor mine have been published previously (Klasner, 1978); permission to publish these data was given at that time by Ford Motor Company.

GEOLOGIC BACKGROUND

The Archean rocks in northern Michigan are overlain by dominantly stratified rocks of the Early Proterozoic Marquette Range Supergroup (Irving and Van Hise, 1892; Van Hise and Bayley, 1897; James, 1958; James, Clark, and others, 1961; James, Dutton, and others, 1968; Cannon and Gair, 1970). The Marquette Range Supergroup (table 1) comprises, from oldest to youngest, the Chocolay, Menominee, Baraga, and Paint River Groups (Paint River Group not shown). Rocks of the Chocolay Group are present at the east end of the exposed foldbelt in Michigan and in the area near Ironwood to the west, but are absent in between.

Previous structural studies (Cannon and Klasner, 1972; Klasner, 1972; Cannon, 1973; and Klasner, 1978) have shown that the Early Proterozoic rocks in the eastern area of this report (fig. 2) were subjected to at least three periods of deformation. These were designated F_1, F_2, and F_3 by these authors; they are designated D_1, D_2, and D_3 in this report for consistency with other reports in this series. The first event (D_1) was thin skinned and resulted in shortening of Early Proterozoic strata and development of a widespread west-northwest-trending structural fabric. The second event (D_2) was postulated to involve block uplift of Archean basement rocks and formation of prominent structural features such as the Marquette and Republic troughs and infolding of Early Proterozoic strata into the troughs. Larue and Sloss (1980) suggested that the troughs started to form early, during deposition of the sediments, and prior to D_1 deformation. Klasner (1972, 1978) noted a third, late-stage, brittle deformational event (D_3) and suggested that it could have been caused by late block uplift of Archean basement. Cannon (1973) divided the regional structures in northern Michigan into "first" and "second" order features. First-order structures have a wide range of orientations and are related to postulated block uplift and doming (Sims and others, 1984; Sims and Peterman, 1976) of the Archean crust. Second-order structures have a consistent west-northwest trend and are related to the D_1 shortening of Early Proterozoic supracrustal strata.

The dichotomy in style of deformation between Early Proterozoic rocks and the underlying Archean rocks led Cannon and Klasner (1972), Klasner (1972, 1978), and Cannon (1973) to suggest that a decollement exists between the Proterozoic and Archean. They suggested that shortening of Early Proterozoic strata relative to underlying Archean rocks was possibly caused by gravity sliding off an ancestral Penokean mountain range to the south. Holst (1982, 1984) proposed an Early Proterozoic nappe structure in the same tectonic environment in eastern Minnesota, and Maharidge (1986) and Sims and others (1987) have suggested that a crystalline-cored nappe structure may exist just north of Iron Mountain, near the Niagara fault (fig. 1).

Three regional metamorphic aureoles have been defined in northern Michigan (James, 1955). All the key areas of this study lie within the chlorite zone (greenschist facies) of the aureoles. Klasner (1978) has shown that peak metamorphism postdates the initial D_1 phase of deformation but predates the second phase. Attoh and Vander Meulen (1984) and Attoh and Klasner (1989) suggested that the nodal metamorphism was the result of tectonic stacking caused by Early Proterozoic overthrusting.

STRUCTURE OF KEY AREAS

All the key areas described herein lie near the northernmost edge of the exposed Penokean orogen in northern Michigan (fig. 1). The wide separation of key outcrops along the strike of the orogen reflects the general paucity of outcrops in this region. In this discussion, we first describe outcrops in the east at the localities clustered near L'Anse, where structural data are more abundant; and we conclude with the Ironwood-Hurley area in the west, where structural data are less abundant.

Falls River Area

Numerous outcrops of graywacke and slate of the Michigamme Formation of the Baraga Group are exposed for a distance of about 1.8 km along Falls River near the village of L'Anse, Mich. (See fig. 2 for location of the outcrop areas discussed herein.) In a detailed structural study of these rocks, Sikkala (1987) identified three phases of deformation. The first phase, herein designated D_1, consists of north-verging regional folds (F_1) in bedding (S_0) with a gentle south-southwest-dipping penetrative foliation (S_1). A roughly coaxial second phase of deformation (D_2) formed generally open chevron folds (F_2) in S_1, and a steeply dipping axial-planar (S_2) fracture cleavage. A third event (D_3) locally deformed S_0, S_1, and S_2 about a northeast-trending fold axis (F_3), forming spaced S_3 cleavage locally. Sikkala (1987) noted that in general, accompanying thrust faults are not exposed, but in places where they are exposed, they are cataclastic zones containing quartz and carbonate minerals.

Stereoplots and diagrams (fig. 3) from Falls River illustrate the nature and sequence of deformation in this locality. Similarly to Sikkala (1987), we conclude that bedding (S_0) has been folded about near-horizontal, west-northwest-trending fold axes (F_1) during the D_1 deformational event (fig. 3*A*). Poles to S_1 foliation (fig. 3*B*) show that it is axial-planar to the F_1 folds, strikes west-northwest, and dips about 15° SW. Bedding is overturned toward the north, and second-order parasitic folds (fig. 3*C*, *D*) lie on the overturned lower limb of a north-verging fold system.

The nature of the second deformation (D_2) at Falls River is illustrated by figure 3*B* and 3*E*: S_1 foliation has been folded into a series of open folds (F_2); F_2 fold axes are nearly coaxial with F_1 axes and plunge gently west-northwest; S_2 foliation is nearly vertical.

A third deformation (D_3) reported by Sikkala (1987) consists of a spaced fracture cleavage (S_3) about which S_2 foliation is reoriented. The S_3 foliation strikes east-northeast and dips steeply southeast. This fracture cleavage is axial-planar to an open fold represented by the gently southwest plunging fold axis (F_3) shown in figure 3*A*. Poles to bedding in the F_3 fold define a great circle which is coincident with the measured F_3 fold axis.

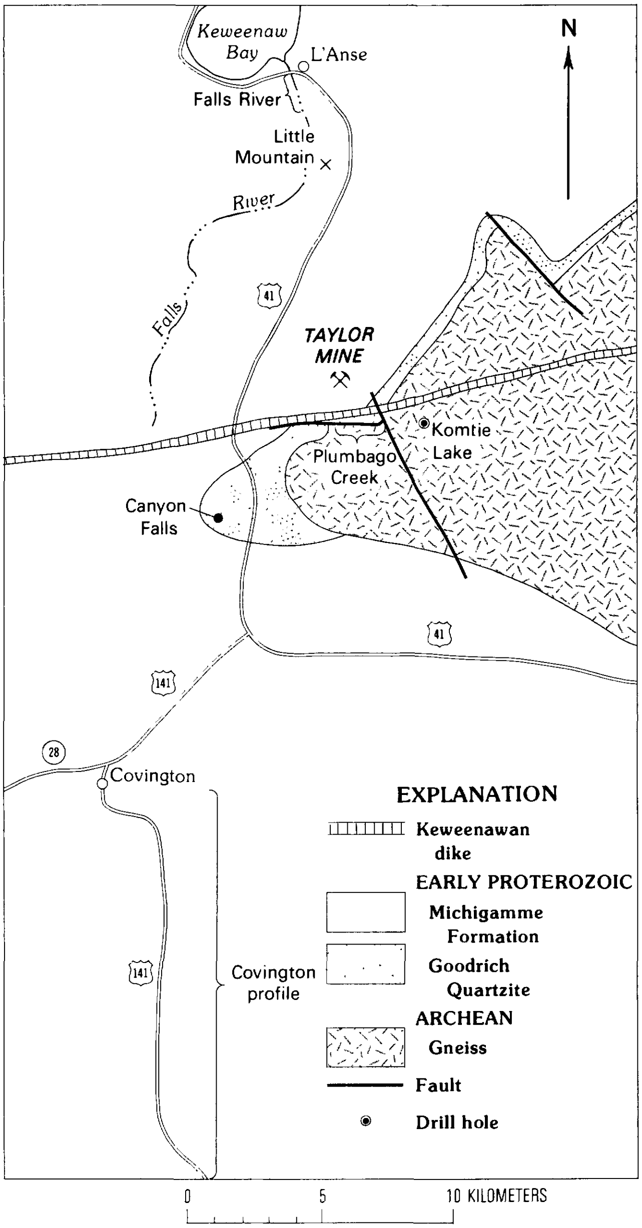


Figure 2. Localities in the L'Anse, Mich., area discussed in the text: Canyon Falls, Falls River, Komtie Lake, Little Mountain, Plumbago Creek, Taylor mine, and Covington profile. The Ironwood-Hurley outcrop area is located about 150 km west of the L'Anse area, as shown in figure 1. (See also fig. 12.) Geology modified from Cannon (1986).

Little Mountain Area

Little Mountain (fig. 2) is a small bedrock hill that stands above the surrounding plain of Pleistocene deposits. An easterly trending 1.1 Ga (Keweenawan) diabase dike is exposed along the crest of the hill and intrudes deformed graded beds of greenschist-facies metagraywacke.

A structural cross section of a part of the east face of Little Mountain (fig. 4*A*) shows that the metagraywacke beds have been deformed into a north-verging asymmetric fold system with axial-planar (S_1) foliation. The overall structure of the cliff face is that of a syncline. A lower hemisphere stereoplot (fig. 4*B*) of poles to bedding (S_0) shows that S_0 is folded about F_1 fold axes that plunge gently N. 75° W. Figure 4*C* shows that S_1 foliation is oriented approximately N. 60° W., 40° SW. At locations I and II in figure 4*A*, S_1 foliation is deformed by a series of chevron folds. This may explain the spread in S_1 foliation in figure 4*C*, but such deformation is not widespread. The long (stretch) axes of constrictively deformed calc-silicate

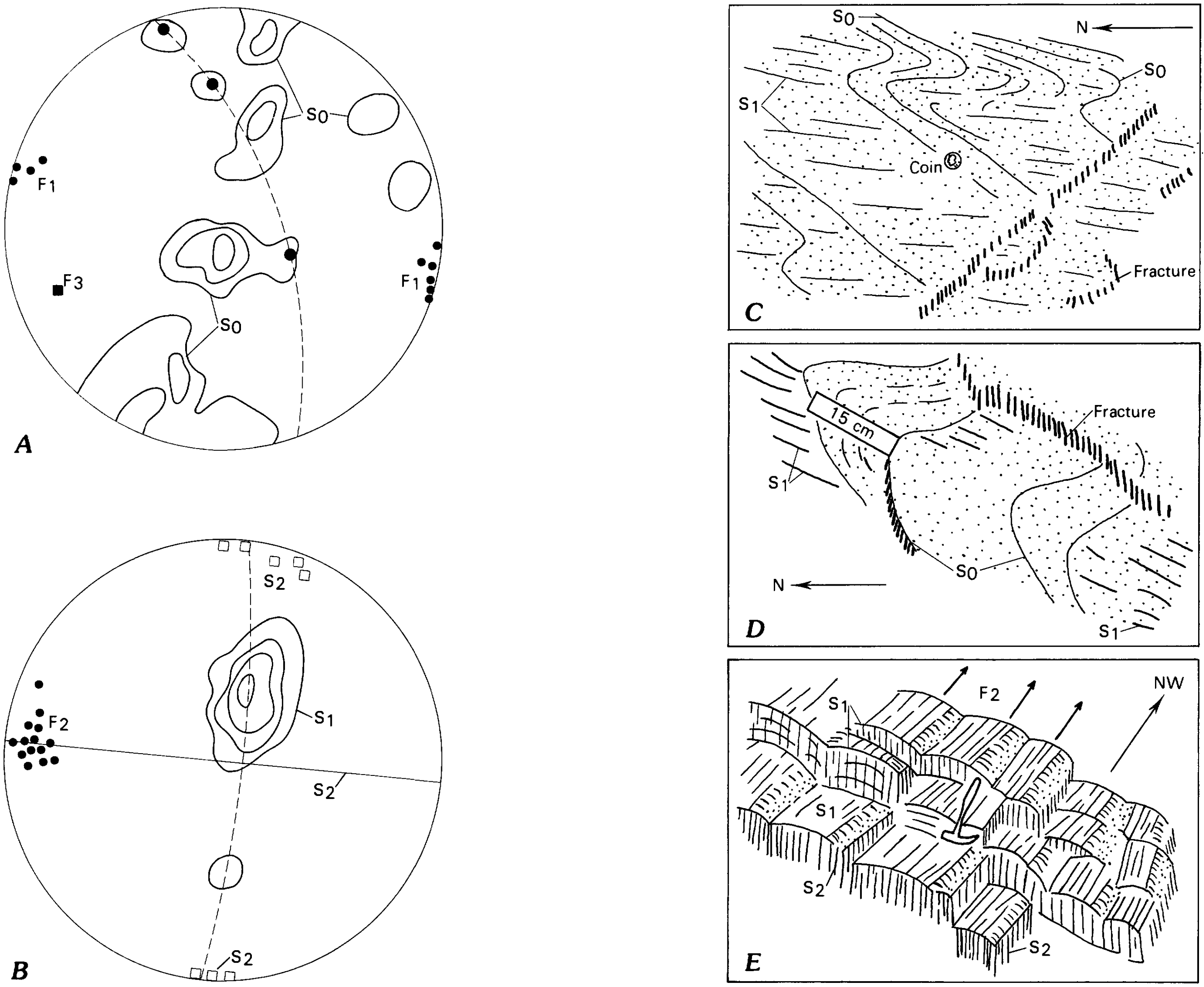
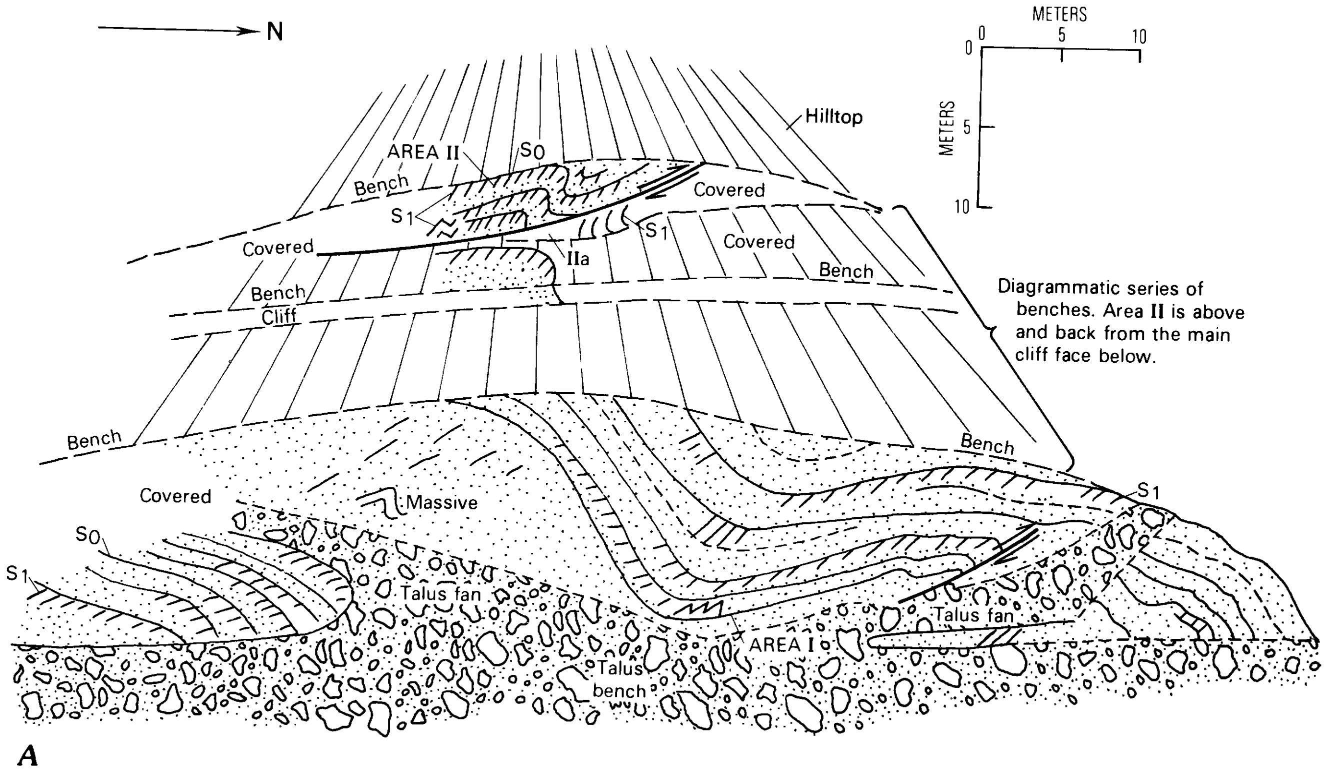


Figure 3. Diagrammatic sketches from field photographs and equal-area lower hemisphere stereoplots, Falls River area, near L'Anse, Mich. *A*, Stereoplot showing 2, 7, and 10 percent contours on 27 poles to bedding. Small dots, axes (F_1) in folds of S_0. Solid square, measured axis (F_3) of an F_3 fold. Large solid dots and great circle (short dashes) define poles to bedding of the F_3 fold. *B*, Stereoplot showing 2, 10, 20, and 30 percent contours on 53 poles to S_1 foliation. Solid dot, F_2 fold axis. Open square, pole to spaced S_2 foliation. Great circle (dashed line) shows folded S_1; vertical S_2 plane is shown by solid line. *C* and *D*, Sketches from photos (both looking east), showing relationship of S_0 and S_1. Country rock is graywacke-slate. *C*, Sketch from photo of vertical face on east side of Falls River near old railroad bridge, just south (upstream) from the bridge on U.S. Highway 41. Coin is 2.5 cm in diameter. *D*, Sketch from photo of vertical face on east side of river, north (downstream) from bridge on U.S. Highway 41. Rule is 15 cm long. *E*, Sketch from photo (looking northwest), showing relationship of S_2 foliation and F_2 fold axes (arrows) to S_1 foliation. Outcrop is north from bridge on U.S. Highway 41. Hammer is 31 cm long.

concretions have a consistent southwesterly plunge, but detailed strain analyses have not been made on them and the stretch axes are not shown on the stereonet plots.

Location II (fig. 4*A*) is on the top of Little Mountain and set back from the main cliff face by a series of benches. Here, and elsewhere on the top of Little Mountain, graded bedding is overturned toward the north. At location II, overturned bedding is juxtaposed to, but not in direct contact with, underlying upright beds that dip 55° NNW. Slickenlines on the underside of a bedding surface at IIA (fig. 4*A*) trend N. 50° E. In the region of the overturned beds, S_1 foliation has been deformed, as diagrammatically shown by the kink-folds (area I, fig. 4).

Little Mountain consists primarily of asymmetric folds with steep short north limbs. Stratigraphic facing is readily discernible on the main cliff face, as shown in figure 4*A*. In contrast to the main cliff face in which bedding is upright, bedding at the top of Little Mountain is overturned toward the north, as shown at location II in figure 4*A*. This difference in nature of deformation may represent a local



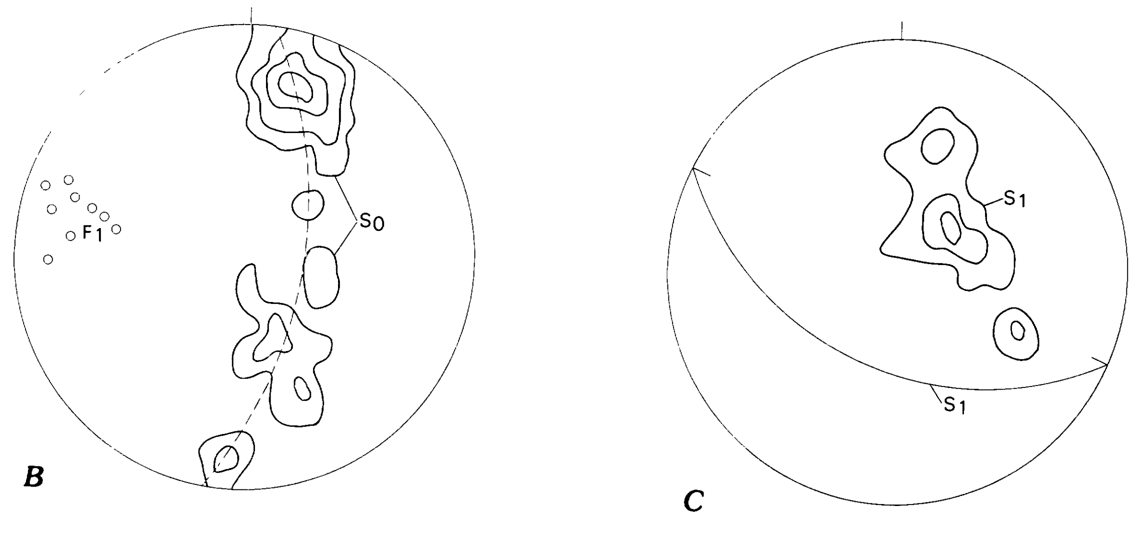


Figure 4. Structure in Michigamme Formation at Little Mountain, northern Michigan. *A*, Field sketch of vertical cliff face along east end of Little Mountain (looking west). Graywacke beds are graded; slaty cleavage (hachure marks) is developed along the tops of the beds; bottoms of beds consist of coarser sandy material. S_0, bedding; S_1, slaty foliation. Triangle pattern, talus. Dashed line, edge of talus. Area I, location of kink folds that affect S_1. Area II, sketch of a small east-facing cliff at the top of Little Mountain. It lies above the main cliff face sketched below, and illustrates overturned bedding. Note also deformed S_1. Heavy line, thrust fault; arrows show sense of movement. *B*, Stereoplot (equal-area lower hemisphere) of bedding (S_0) and measured F_1 fold axes. Contours at 2, 6, 12, and 20 percent on 49 poles to bedding (S_0). Great circle (dashed line) represents orientation of folds in bedding that define F_1 fold axes. *C*, Stereoplot (equal-area lower hemisphere) of S_1 foliation that is axial-planar to folds in S_0. Contours are at 4, 6, and 10 percent on 25 poles to S_1. General orientation of S_1 plane shown by solid curved line.

inhomogeneity in folding caused by a slip along the bedding. More likely, however, the overturned beds lie above a small thrust fault (fig. 4*A*, location II) that is subparallel to the gently south dipping beds of the asymmetric folds. The thrust fault may represent late D_1 deformation, or possibly the second (D_2) deformation.

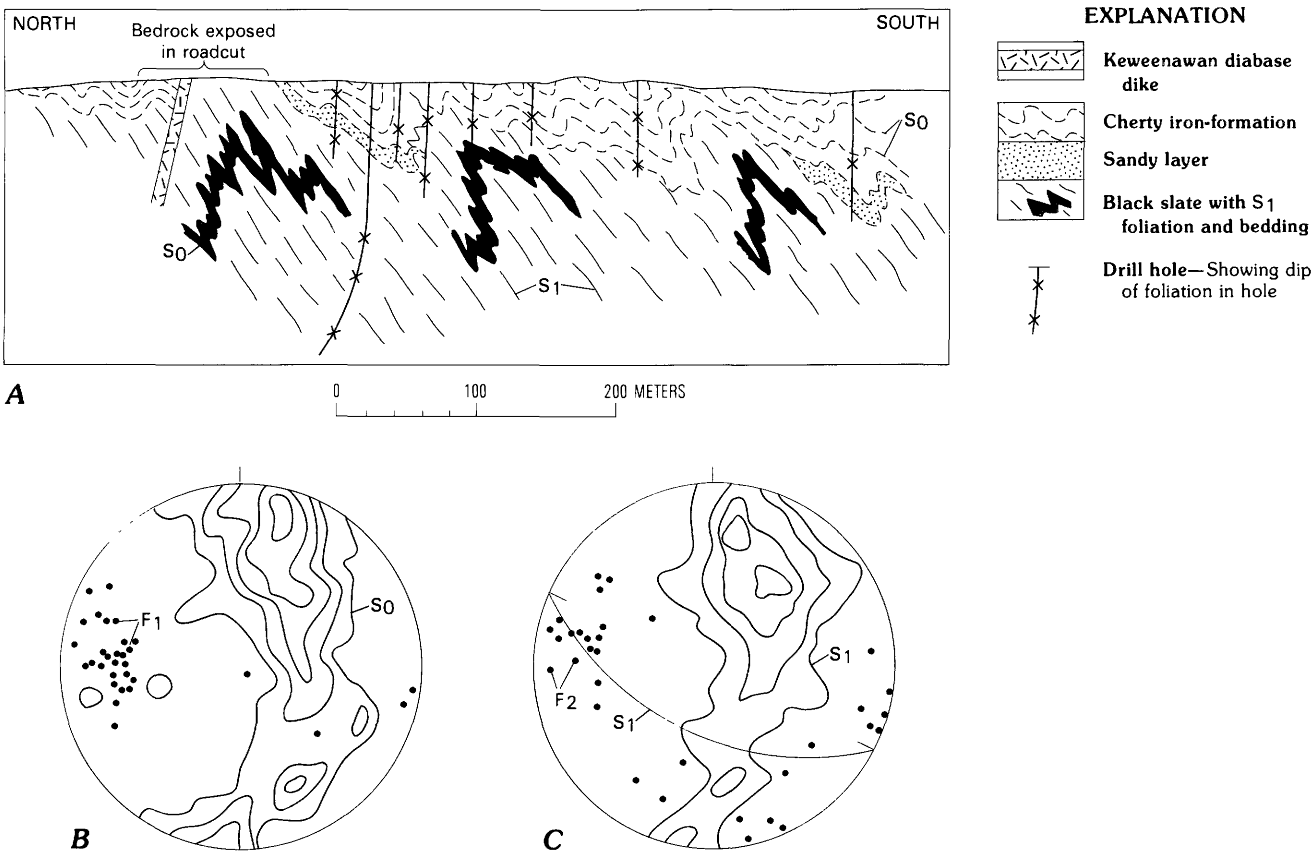


Figure 5. Geologic cross section and equal-area lower hemisphere stereoplots from Taylor mine area, northern Michigan. Modified from Klasner (1972, 1978). *A*, Interpretive cross section constructed from roadcut and drill cores showing north-verging overturned folds. Dip of foliation in drill cores is shown in two directions to signify that the drill core is not oriented. All exposed rocks in area have south-dipping foliation. *B*, Stereoplot of 204 poles to bedding (S_0). Dot, orientation of F_1 fold axis. Contours at 0.5, 1, 2, 6, and 8 percent. *C*, Stereoplot of 236 poles to S_1 foliation and general orientation of S_1 plane of foliation (solid line). Dot, orientation of F_2 fold axis. Contours at 0.4, 2, 5, and 9 percent.

Taken together, the southwest-plunging stretch lineations as expressed by long axes of the calc-silicate concretions, the north-verging folds, southwest-dipping S_1 foliation, and the northeasterly oriented slickenlines on bedding indicate a northeast sense of tectonic transport at Little Mountain.

Taylor Mine

Rocks in the locality of Taylor mine (location, fig. 2) consist of deformed phyllite, chert, iron-formation, and graphitic slate of greenschist metamorphic grade that were deformed by at least three events (Klasner, 1972, 1978). The first deformation (D_1) folded bedding (S_0) into a series of folds (F_1) that have a wavelength of about 250 m and an axial-planar (S_1) foliation (fig. 5*A*); F_1 fold axes plunge gently northwest (fig. 5*B*). Bedding is overturned toward the north, and S_1 cleavage is generally oriented N. 66° W., 55° SW., as shown in figure 5*C*. Deformation D_2 deformed S_1 into a series of open chevron folds (F_2) with gently northwest plunging F_2 fold axes that are roughly coaxial with F_1 fold axes. Spaced (S_2) fracture cleavage generally dips northeast but is scattered in orientation. Faint crenulation lineations on S_1 surfaces lie at an angle to F_2 and provide evidence for a third deformation (D_3) at Taylor mine.

Plumbago Creek

The Plumbago Creek locality (fig. 2) is south of Taylor mine, along the contact between Archean gneiss and Early Proterozoic metasedimentary strata. The area comprises Archean quartzofeldspathic gneiss to the south, Early Proterozoic graphitic slate (exposed in an open pit graphite mine) to the east, Early Proterozoic iron-formation, and an undeformed 1.1 Ga (Keweenawan) diabase dike to the north (fig. 6). Structural data from the slate exposed in the graphite pit indicate at least three stages of deformation (D_1, D_2, D_3). As shown in figure 7*A*, the most prominent foliation (S_1) strikes west-northwest and dips moderately to steeply southwest. Axes of folds (F_1) in bedding (S_0) are shown in figure 7*A*. The great circle with accompanying F_{2a} fold axis indicates that S_1 has been folded during D_2

deformation. Small (millimeter wavelength) crenulation folds (F_2) on S_1 are roughly parallel to the N. 85° W. fold axes (see coincident F_2 and F_{2a}, fig. 7*A*) and may represent D_2 folding. Other crenulation fold axes (not shown) that are roughly perpendicular to the strike of S_1 may represent F_3 fold axes.

Structural data from the Archean gneiss provide additional information on deformation at the Plumbago Creek locality. The relationship between Archean gneissic foliation (S_A) and Early Proterozoic foliation (S_2) can be observed at location 107 in figure 6 and is shown in figure 7*B*. Here, Archean gneissic foliation (S_A) was folded during the second (D_2) deformation about a shallow west-northwest-plunging fold axis (F_2 in fig. 7*C*). Poles to Archean gneissic foliation tend to lie along a great circle that has a west-northwest-plunging axis (F_{2a} in fig. 7*C*), and most F_2 fold axes or S_2-S_A intersection lineations (L_{2x}) plunge gently west-northwest or south-southeast.

Prominent mylonitic foliation occurs along Plumbago Creek in the western part of the map area (locations 121 and 124, fig. 6). Figure 7*D* is a plot of poles to mylonitic foliation and shear zones around Plumbago Creek. The poles plot in two groups: one group, designated S_2, defines a moderate to shallow south-dipping foliation, whereas the other group (S_3) defines a west-southwest-dipping set. These distinctly different orientations and the crosscutting relationship of the north-northwest set (S_3) relative to S_2 (fig. 6, also fig. 7*F*) indicate that S_3 postdates S_2 foliation.

The S_2 mylonitic foliation has approximately the same strike as the S_1 foliation in the graphitic slate (and also at Taylor mine, Little Mountain, and Falls River), but it is fundamentally different than S_1. S_1 foliation in the Early Proterozoic rocks in the L'Anse area in general has been deformed, as at Taylor mine and Falls River, by open chevron folds having F_2 fold axes and S_2 fracture cleavage. F_2 axes are typically coaxial with F_1 fold axes. In contrast, the mylonitic east-northeast foliation in Archean rocks (S_2, fig. 6) is not deformed and does not appear to have undergone a second major deformation.

Although we cannot prove conclusively from the Plumbago Creek area alone that the easterly trending mylonitic foliation postdates S_1 foliation, previous work in the general region suggests that it does. Cannon and Klasner (1972), Cannon (1973), and Klasner (1978) have shown that S_1 foliation has a consistent west-northwesterly orientation, but a similar Early Proterozoic foliation is lacking in Archean rocks. For this reason, Cannon and Klasner suggested that D_1 was a thin-skinned deformational event, and they suggested that a decollement must detach Early Proterozoic D_1-deformed strata from the Archean basement.

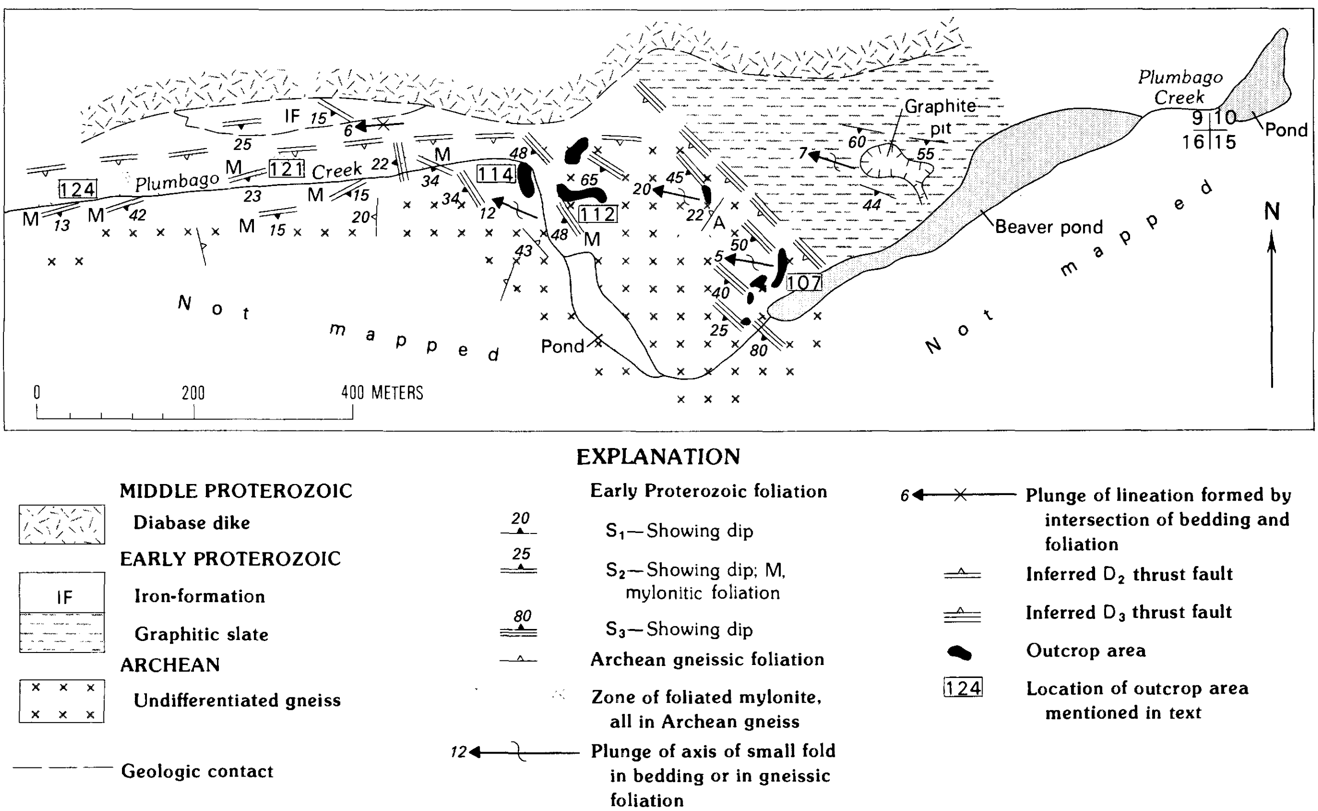


Figure 6. Geologic map in area of Plumbago Creek and graphite pit south of Taylor mine, northern Michigan. Blank areas are covered, not mapped. Area of published map of Taylor mine locality (Klasner, 1972, 1978) lies to north.

Recent studies by Nachatilo and Bauer (1990) in the Marquette trough region confirm the absence of Early Proterozoic structures in Archean basement rocks of that area. Evidence for D_2 deformation, however, is commonly observed along the contact between Early Proterozoic strata and Archean rocks. The D_2 deformation is generally (though not always) marked by a reverse fault, with associated sheared Archean rocks.

As in the Plumbago Creek area, foliated rocks of faulted Archean-Proterozoic contacts have not been deformed by subsequent deformation, as have the foliated Early Proterozoic rocks. Thus, inasmuch as the mylonitic rocks at Plumbago Creek were not deformed by a second coaxial deformation (D_2) as were the Early Proterozoic rocks to the north, we conclude that the mylonitic rocks along Plumbago Creek were formed during a second (D_2) deformation.

Rocks within the mylonitized shear zone range from protomylonite to mylonite with more than 75 percent recrystallized fine-grained matrix. (See Wise and others, 1984.) The mylonites consist primarily of sericite, quartz, and feldspar. S-C fabric and quartz-sericite fish structures (fig. 7*E*) at location 124 within the mylonite indicate a northward sense of vergence. The mylonitic foliation in the Early Proterozoic rocks dips southward beneath Archean gneiss.

The north-northwest-trending shear zones (S_3) appear to be localized along an offset in the general east-west structure along Plumbago Creek. They are mainly expressed by the north-northwest-trending foliation (S_3) at location 114 in figure 6. A sketch from a photo at outcrop 114 (fig. 7*F*) shows the nature of these shears; they strike about N. 30° W. and dip steeply southwest. The shear zones crosscut and deform the S_2 shear zones in the Archean rocks. We interpret these shears to be caused by the third (D_3) deformational event. S–C fabric data from near the north-northwest-trending D_3 shear zones at location 112 (fig. 6) indicate an east-northeast sense of tectonic transport (see fig. 7*G*).

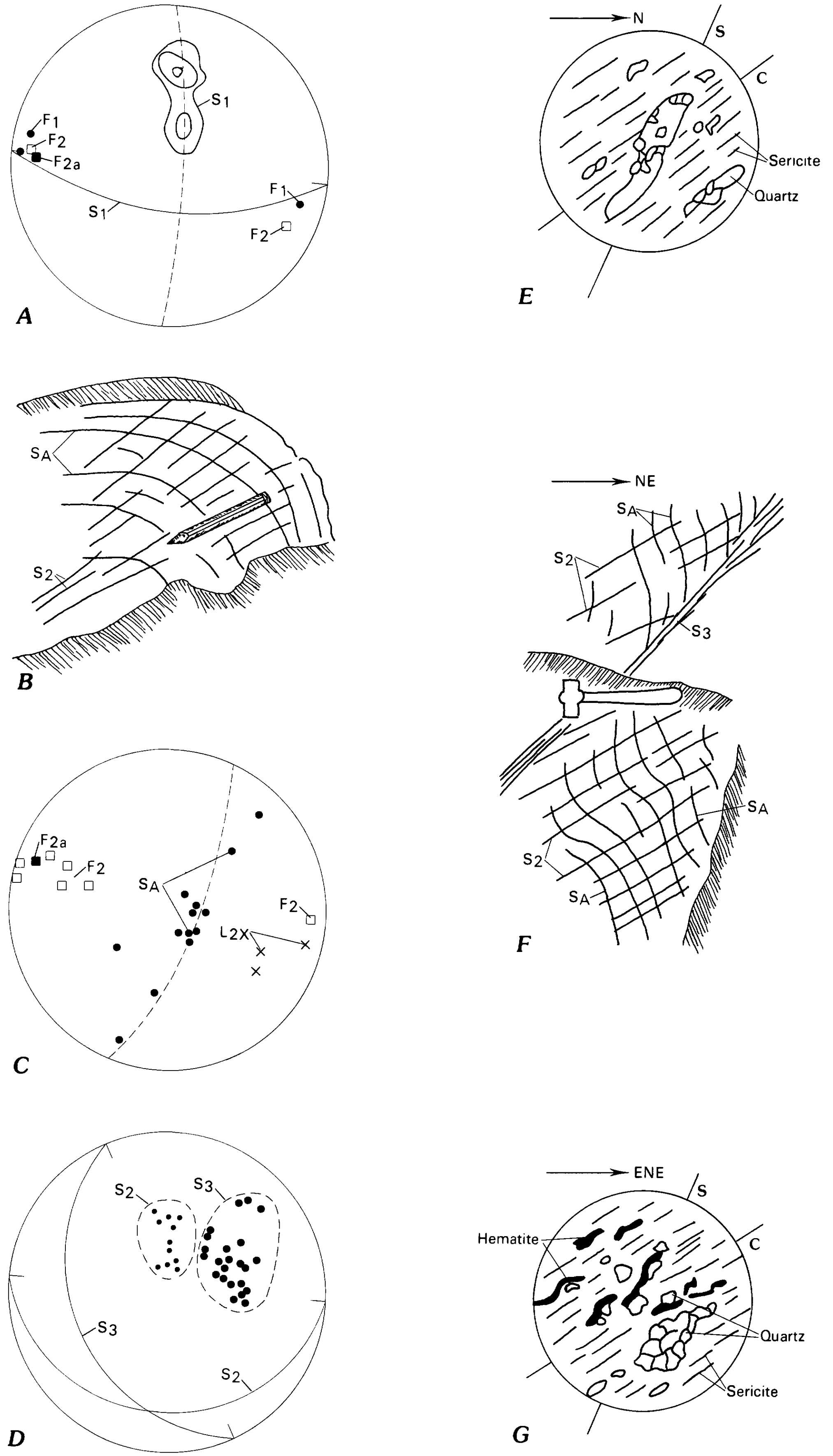
In summary, rocks in the Plumbago Creek area were subjected to at least three stages of deformation: D_1 formed an S_1 foliation and F_1 fold axes in Early Proterozoic slate (as exposed in the graphite pit); D_1 was thin skinned and affected only Early Proterozoic rocks. A second event (D_2) deformed S_1 and Archean foliation S_A, and resulted in S_2 foliation and F_2 fold axes. It also formed prominent west-northwest-trending, south-dipping mylonite fault zones (S_2) in the Archean gneiss along the contact between Early Proterozoic slate and the gneiss. The Archean gneiss block was thrust northward during D_2 and deformed the S_1 foliation in the Early Proterozoic slates. A third event (D_3) formed north-northwest-trending, southwest-dipping faults in Archean gneiss that crosscut the D_2 fault zones. East-northeast movement of Archean rocks along these faults caused isolated zones of S_3 foliation.

Komtie Lake

A drill hole started in Archean gneiss at Komtie Lake (fig. 2) provides further data concerning the structural evolution of the L'Anse area. Figure 8*A* is a geologic sketch map of the Komtie Lake area, which lies near the northwest edge of a block of Archean gneiss (northern complex, fig. 1). (For more detail on the regional geology, see the geologic map of the Iron River 1°×2° quadrangle (Cannon, 1986).) Archean gneiss in scattered outcrops has a variable foliation that dips generally to the southwest. Komtie Lake is surrounded by a low swampy area; an undeformed 1.1 Ga Keweenawan diabase dike forms a prominent ridge north of the lake and crosscuts the gneissic foliation.

The 210-m-deep Komtie Lake drill hole (fig. 8*B*) penetrated, from the top downward, 30 m of Archean mafic to felsic gneiss and 3 m of mylonite, followed by phyllitic slate, iron-formation, and weakly deformed quartzite. The latter three rock types are similar to Early Proterozoic strata at Taylor mine, Canyon Falls, and other nearby areas where they stratigraphically overlie the Archean gneiss. We

Figure 7 (facing page). Structure in Plumbago Creek area, northern Michigan. All stereoplots are equal-area lower hemisphere plots. *A*, Contoured stereoplot of 20 poles to S_1 foliation at graphite pit. Contours at 5, 20, and 40 percent. Great circle (solid line), general orientation of S_1; F_1 fold axis in bedding shown by solid dot (F_1). Square, orientation of F_2 crenulation fold axis (F_2) on S_1 foliation planes. Great circle (dotted line) shows folded S_1 surfaces. F_{2A}, which coincides with F_2, is fold axis to the S_1 great circle. *B*, Cross-sectional sketch from a field photograph at location 107 (fig. 6) of an F_2 fold in Archean foliation (S_A). Axial-planar foliation shown by S_2. Pencil is 16 cm long. *C*, Stereoplot showing poles to foliation (S_A) in Archean gneiss. Open square, orientation of F_2 fold axis (F_2) in Archean foliation; X, orientation of intersection lineation (L_{2X}) of S_2 axial-planar cleavage and Archean foliation (S_A). F_{2A} is fold axis that corresponds to the great circle. *D*, Stereoplot of mylonitic foliation and shear bands in Archean gneiss, which can be divided into two sets: (1) S_2 defines an easterly oriented set (general orientation of S_2 plane is shown by great circle), and (2) S_3 shows north-northeasterly oriented set (general orientation of S_3 plane shown by great circle). *E*, Sketch of microscopic view (vertical slab) of a deformed quartz grain in mylonite at location 124 (fig. 6). Lines indicate S_2 sericitic foliation. Quartz grain is partly recrystallized to a finer grain size (mortar structure), and its shape shows S–C fabric orientation and northward sense of vergence. Field of view 3.3 mm in diameter. *F*, Cross-sectional sketch of photograph of an S_3 shear band at location 114 (fig. 6). S_3 shear band crosscuts S_2 foliation and S_A (Archean gneissic) foliation. Curvature of S_A suggests an east-northeast sense of tectonic transport during D_3 deformation. Hammer approximately 45 cm long. *G*, Sketch of microscopic view (vertical slab) of recrystallized quartz grain that has been deformed, from location 112 (fig. 6); shows an east-northeast sense of tectonic transport. Heavy line, hematite; some with sigmoidal patterns that also indicate east-northeast tectonic transport. Sericite (light line) is generally parallel to the C-fabric orientation. Field of view 3.3 mm in diameter.



S1
F1
F2
F2a
S1
F1
F2
A
N
S
C
Sericite
Quartz
E
SA
S2
B
NE
SA
S2
S3
SA
S2
SA
F
F2a
F2
SA
F2
L2
C
S2
S3
S3
S2
D
ENE
S
C
Hematite
Quartz
Sericite
G

interpret the Archean gneiss as having been thrust over the Early Proterozoic strata. Dip of the foliation in the drill core is approximately 35° to 40°, about the same as most of the south-southwest-dipping foliations in surface exposure at Komtie Lake. A fold in foliation (fig. 8*A*) within a greenstone layer in the gneiss plunges 30° south-southeast, and the asymmetry of the fold indicates east-northeast vergence.

Based on data from the nearby Plumbago Creek area, we interpret the mylonitic zone at the base of the gneiss to be a D_2 or D_3 feature. Because the core is not oriented, only the magnitude of dip, and not the strike, of the foliation is known. The east-northeast-verging structures are interpreted as D_3, similar to those at Plumbago Creek. The D_3 event is also interpreted as having caused the shallow, south-southeast-plunging fold in the Archean greenstone.

Canyon Falls

A shallow canyon cut into subhorizontal Early Proterozoic quartzite west of the Archean northern complex (fig. 2) provides additional information on the structural history of the Penokean foreland area. The quartzite lies unconformably (fig. 9) on Archean gneiss (Klasner, 1978; Cannon, 1986). Cannon (1986) interpreted this quartzite as the stratigraphic equivalent of the Goodrich Quartzite, which occurs in unconformable contact with Archean basement in much of the western Marquette Range. It is less intensely deformed than other Early Proterozoic strata that overlie it in the region. Microscopic examination of the quartzite shows that it consists of 70 percent quartz grains that are 1–2 mm in diameter and embedded in a fine-grained matrix of sericite and quartz. Only some quartz grains are clast supported. The larger grains show moderate undulatory extinction and their long axes tend to have a preferred orientation. The less intensely deformed nature of the quartzite may indicate that it is separated from younger, intensely deformed Early Proterozoic strata (exposed only 6 km away at Taylor mine) by a decollement.

Structural data from the quartzite reveal at least one period of deformation. A thin pelitic layer within the thick-bedded quartzite has a distinct S_1 and (or) S_2 foliation oriented N. 75° W., 35° SW. (figs. 9 and 10). The thicker quartzite layers have a similarly oriented faint foliation. Slickenlines on bedding planes near the pelitic layer trend N. 5° E. Intersection of S_0 bedding and foliation yields a fold axis oriented 10°, S. 65° W.

An outcrop at the contact of sheared quartzite on the south and metagraywacke (slate unit in fig. 9) on the north occurs 2 km north of Canyon Falls. Foliation in the sheared graywacke is oriented N. 52° W., 45° SW. Bedding in quartzite about 100 m south of this outcrop is subhorizontal, similar to that at Canyon Falls. Spaced fracture cleavage in the quartzite is oriented N. 60° W., 62° SW., similar to cleavage in the graywacke.

Data from Canyon Falls indicate at least one deformation that formed a foliation, especially in the thin pelitic layers, and a weak foliation in the massive quartzite. The precise age of the deformation is not known. No evidence exists to suggest that the foliation has been

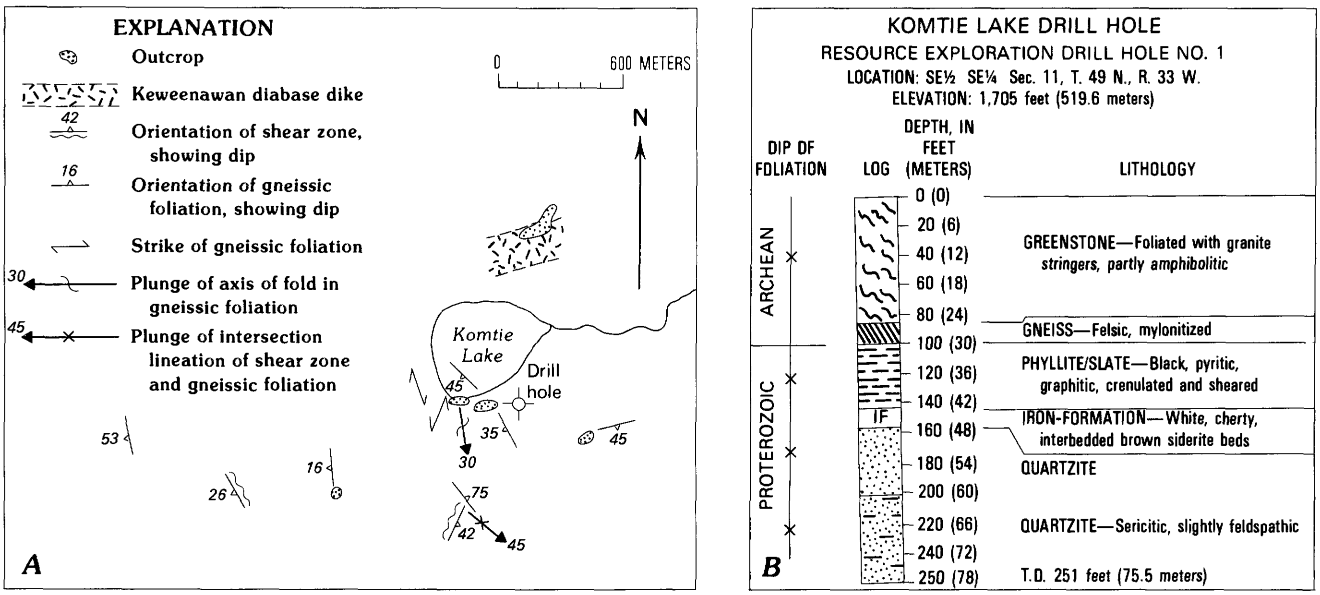


Figure 8. Geologic map and drill-hole data at Komtie Lake area, northern Michigan. *A*, Geologic sketch map of Komtie Lake area showing location of structural measurements and drill hole. *B*, Log of core from Komtie Lake drill hole (logged by R.W. Ojakangas). Dip of foliation in drill core is shown in two directions to signify that drill core is not oriented and true orientation of foliation is not known.

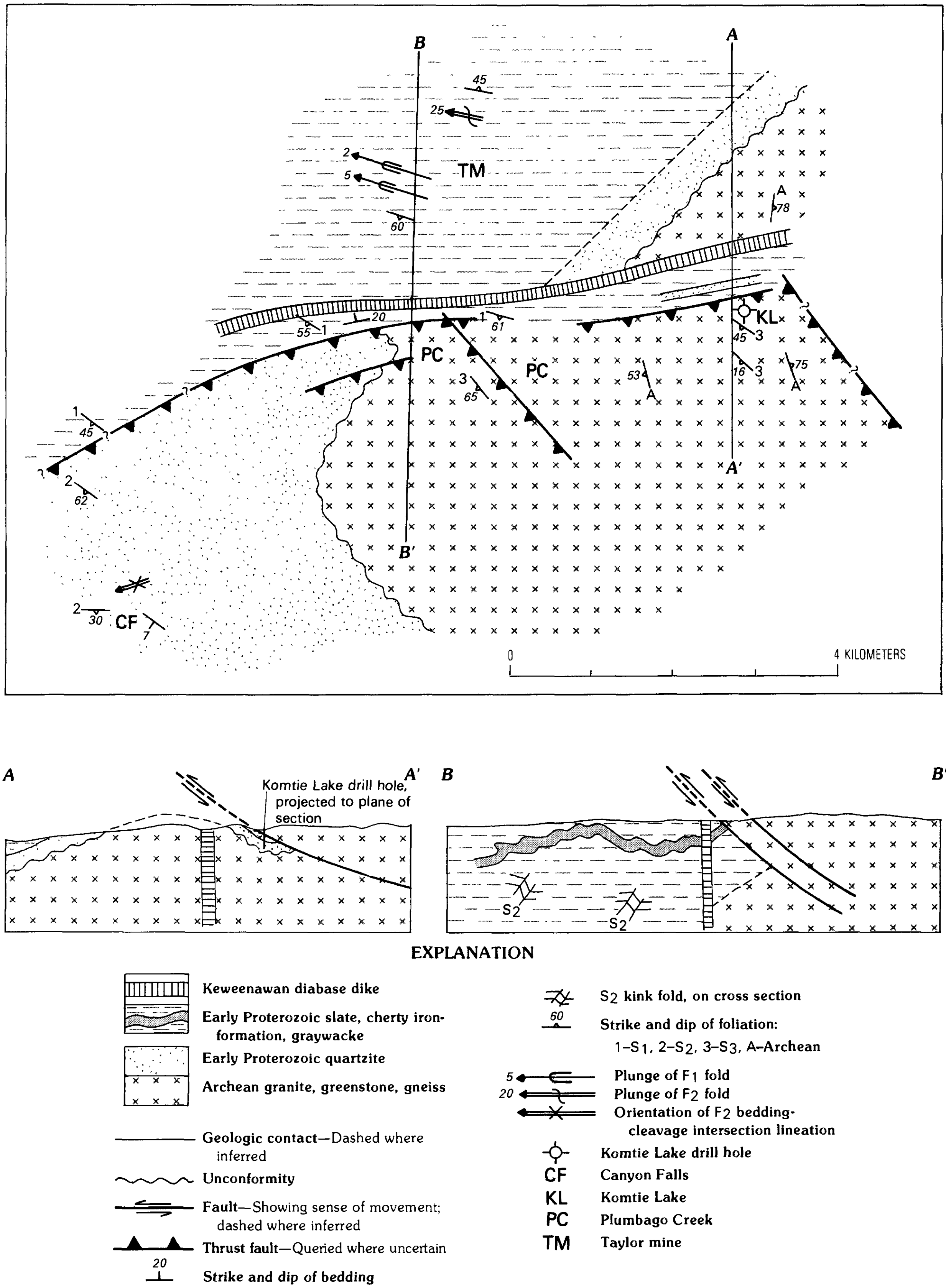


Figure 9. Geologic sketch map and cross sections of Taylor mine, Komtie Lake, Plumbago Creek, and Canyon Falls areas, northern Michigan.

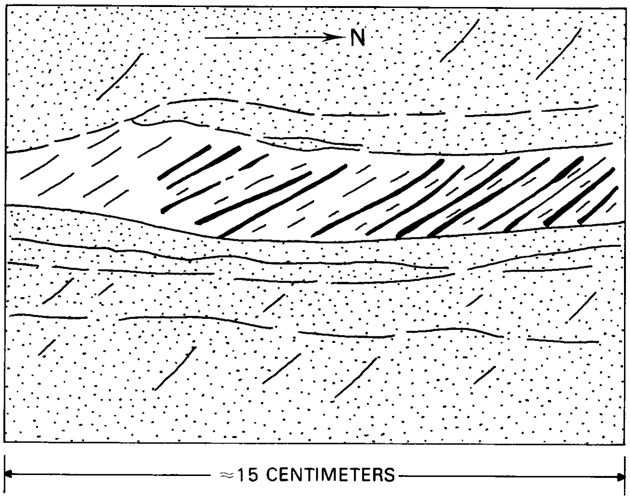


Figure 10. Cross-sectional sketch from field photograph of vertical face at Canyon Falls showing penetrative foliation in pelitic layer (lined) intercalated with massive quartzite (stippled). The quartzite has a faint south-dipping spaced foliation.

refolded, and we therefore tentatively interpret it as S_2, formed during D_2; but it may be D_1 in age. The tectonic slickenlines represent slip along the bedding of the gently dipping quartzite.

Covington Profile

The Michigamme Formation is exposed in several roadcuts along U.S. Highway 141 for a distance of about 16 km south of Covington, Mich. (fig. 2). Outcrops comprise graded beds of graywacke and slate at greenschist metamorphic grade. These beds have a cleavage that is refracted across bedding, and they contain numerous deformed calc-silicate concretions. Figure 11 illustrates the general style of deformation in the outcrops along the profile. Bedding generally strikes west-northwest and dips gently to steeply south. Locally, bedding is overturned toward the north. Folds in bedding range from open to closed, become progressively upright toward the south, and have axes that generally plunge gently west-northwest. A prominent cleavage dips steeply south and is axial-planar to folds in bedding. Some calc-silicate concretions have been deformed into ellipsoids with long axes that plunge generally south. A minor, second, west-trending and steeply south dipping foliation occurs in places along the profile and produces pencil slate with steeply south dipping intersection lineations. Kink bands deform the major foliation in places. At the south end of the profile (fig. 11), foliation is vertical, and it is deformed by a late, north-verging fault that has sigmoidally deformed quartz bands within the fault zone.

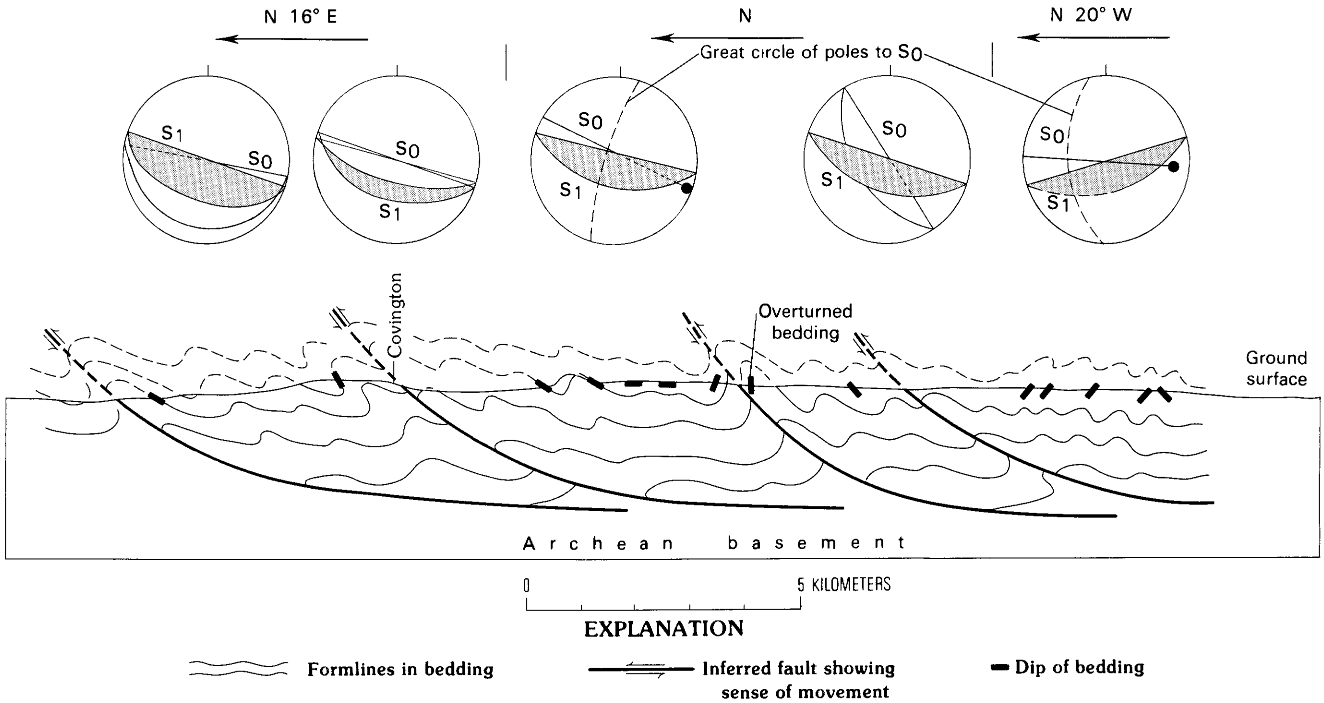


Figure 11. Structural data for Early Proterozoic strata of Michigamme Formation along the Covington profile, northern Michigan. (See fig. 2 for location.) Lower hemisphere stereoplots show orientations of S_1 foliation and bedding (S_0) and fold axes (solid dot) along profile. Faults along profile are inferred at structural breaks. A hypothetical detachment fault separates the Early Proterozoic supracrustal rocks from deeper Archean basement. Configuration of ground surface is at true vertical scale, but formline beds and faults are not meant to infer true thickness of the Early Proterozoic section, which is unknown in this area.

Structural data indicate a single north-verging fold event (fig. 11). The faults shown on the profile are inferred; none were observed in the field, and their locations are based on discontinuities in structures along the section. Apparently, the north-verging faults do not involve Archean basement rocks.

The major structures along the Covington profile are interpreted as D_1 features. The prominent south-dipping foliation (S_1) and associated folds (F_1) were moderately deformed by younger events. Possibly the second foliation that formed the pencil slates is a continuum of the D_1 event, but the kink folds may be D_2 in age or possibly D_3.

Ironwood-Hurley Area

At the far west end of the area of this study, structural data from an outcrop of Early Proterozoic Tyler Formation on U.S. Highway 2 on the Michigan-Wisconsin border, about 150 km west of the Canyon Falls area (fig. 1), provide additional evidence for a north-verging deformational event. The Tyler Formation consists of packets of dark-gray quartzose graywacke beds containing minor slate interbeds intercalated with units of argillaceous siltstone and slate. It is generally believed to be the stratigraphic equivalent of the Michigamme Formation to the east (James, 1958; this report, table 1).

Bedding at the Tyler exposure on Highway 2 is oriented N. 75° E., 70° NW.; a prominent more shallowly dipping cleavage in the argillite is oriented N. 75° E., 58° NW. Flute casts on graywacke soles and graded beds at the highway location show that bedding tops northwest and is upright (fig. 12). Exposures of Tyler strata along strike have similar cleavage-bedding relationships. The regional structural setting of the Tyler Formation is shown in Sims, Peterman, Zartman, and Benedict (1985, fig. 1).

The Tyler strata are part of a large north-dipping homocline (fig. 13*A*) related to the 1.1 Ga Midcontinent rift (Wold and Hinze, 1982). Keweenawan basalt flows above the Tyler strata (fig. 13*A*) dip similarly to bedding in the Tyler. Hendrix (1960) and Schmidt and Hubbard (1972) attributed the steeply north dipping orientations in the Tyler strata to tilting during formation of the Midcontinent rift. Likewise, Alwin (1976) noted that the cleavage cannot be axial-plane cleavage developed in response to the same forces which tilted the Tyler to its present attitude. The cleavage must have been formed prior to Keweenawan tilting of the Tyler strata.

Reorientation by rotation through 70° around strike of the Keweenawan flows restores the Tyler strata to its probable pre-Keweenawan, subhorizontal orientation, and restores the foliation to a gentle southward dip and strike of N. 75° E. (fig. 13*B*). We suggest that this is additional evidence for a north-verging structural deformation event.

Recent studies by Cannon and others (1990) provide further data on the northward tilting of the Tyler strata.

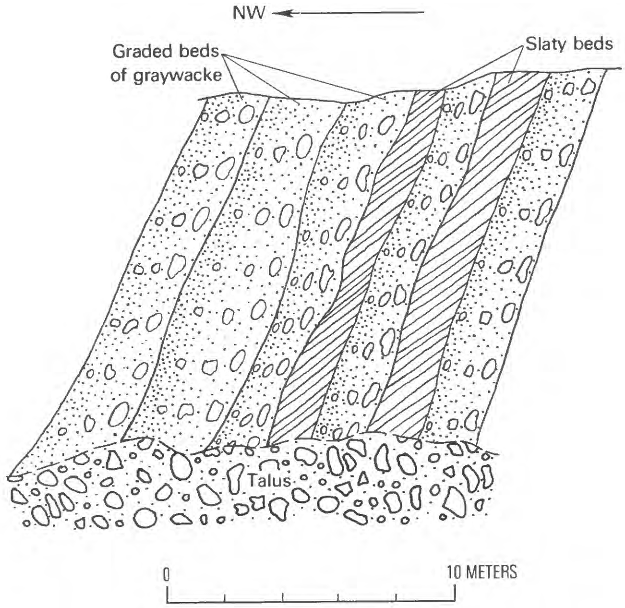


Figure 12. Structural data from the Ironwood, Mich.–Hurley, Wis., area. Sketch from field photograph of the Tyler Formation, subvertical roadcut on U.S. Highway 2. Massive sandy to silty graywacke beds have intercalated silty and argillaceous (slaty) layers. Argillaceous layers have a foliation that dips north, less steeply than bedding. Graded bedding has been diagrammatically added to indicate that bedding is upright. Beds were tilted northwest during Keweenawan rift event.

From studies of rotated Early Proterozoic dikes and 1.1 Ga Rb-Sr ages of biotite from Archean and Early Proterozoic rocks, Cannon and others have suggested that the Archean and Early Proterozoic strata in the region were rotated northward along a north-dipping listric fault that formed during the 1.1 Ga Keweenawan rift event. They suggested that this fault (named the Marenisco fault) lies some 35 km south of the Tyler location and south of the Puritan batholith. The location of this fault was based largely upon appearance of older (pre-1.1 Ga) biotite ages outside (south of) the zone of rocks that were rotated and uplifted during a late compressional event that affected the Midcontinent rift.

GEOLOGIC INTERPRETATION

Table 2 summarizes the structural data presented in preceding sections. At least five and possibly six of the localities described were affected by D_1 deformation; all have evidence for D_2 deformation; and four have evidence for D_3 deformation. We discuss the geologic significance of each of the three phases of deformation following.

D_1 Event

Deformation D_1 is characterized primarily by north-verging folding and thrust faulting. Orientation of F_1 fold axes and strike of S_1 foliation are roughly parallel to the

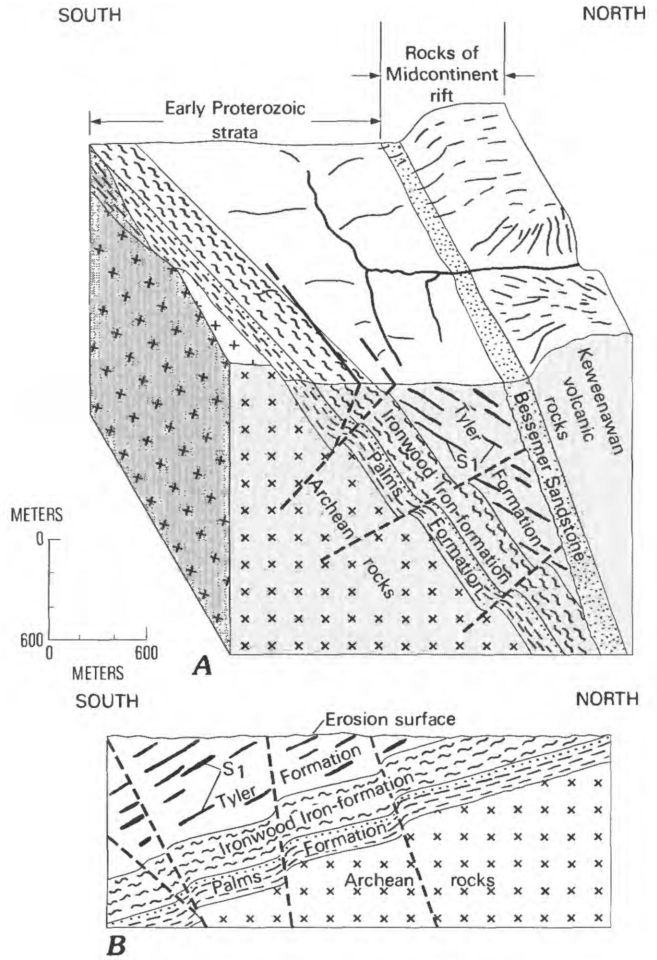


Figure 13. Generalized block diagram and cross section illustrating structural relationships in Ironwood, Mich.–Hurley, Wis., area. Heavy dashed line, fault. *A*, Block diagram showing relationship of pre-Keweenawan strata to rocks of Midcontinent rift. Note that S_1 foliation in Tyler Formation dips less steeply than bedding. Modified from Schmidt and Hubbard (1972). *B*, Reconstructed post-Penokean, pre-Keweenawan position of the strata shown in *A*. Cross section is on same surface as front of block in *A*. Note gently south dipping S_1 foliation. Modified from Schmidt and Hubbard (1972).

easterly oriented axis of the Penokean orogen in Michigan. In the eastern group of outcrops, this phase of deformation seems to affect only Early Proterozoic strata, and we suggest that in this area D_1 was a thin-skinned deformational event. A detachment fault or decollement must lie within the Early Proterozoic strata because Early Proterozoic quartzite at Canyon Falls is only weakly deformed and is unconformably attached to underlying Archean rocks. Yet stratigraphically younger rocks in the region are intensely deformed. The shape of folds, as well as stratigraphic facing directions in folded Early Proterozoic strata at Falls River, Little Mountain, and along the Covington profile, indicates northward structural vergence.

We tentatively interpret as $D_1$the gentle south-dipping foliation in the Ironwood-Hurley outcrop of the Tyler strata (which now has a steep northerly dip due to rotation during formation of the Midcontinent rift—see fig. 13*A*). Structural data in the Ironwood-Hurley area are limited, and the relationship of the Tyler strata to underlying rocks of the Archean Puritan batholith is not known. However, the gentle south-dipping foliation (S_1) and near-horizontal bedding (S_0; and fig. 13*B*) appear to be part of a north-verging deformational system, similar to that present in the Michigamme Formation at Falls River near L'Anse.

At Newport mine, about 7 km south and east of the Tyler outcrop near Ironwood-Hurley, the Palms Formation of the Menominee Group (table 1) is in unconformable contact with the underlying rocks of the Archean Puritan batholith. Although argillaceous and thinly bedded in places, the lower two-thirds of the Palms Formation (Ojakangas, 1983) contains no observable evidence of Early Proterozoic deformation at this location. The unconformable contact dips steeply (≈60°) north, and the bedding in the Palms is parallel to the contact; small clasts of igneous rock are present in the lower few centimeters of the sedimentary rock. However, the Palms and other Early Proterozoic strata are somewhat deformed elsewhere in the region. North-verging folds with gently plunging fold axes and steeply south dipping axial-planar foliation are present at Wakefield, Mich., about 18 km east of the Tyler outcrop. Also, Schmidt (1980) reported that although evidence for folding in the Tyler Formation is meager (observed at only a few places underground), the Ironwood Iron-formation of the Menominee Group, which lies stratigraphically below the Tyler (table 1), has drag folds with gentle northwest-plunging fold axes. The sense of vergence on the drag folds is not known.

Thus, in this western area the Early Proterozoic section consists of undeformed or weakly deformed basal units that are overlain by more intensely deformed strata. A similar deformation pattern characterizes the quartzite at Canyon Falls near L'Anse, which unconformably overlies the basement gneiss. It is possible that the Palms Formation at the Newport mine may be separated from the overlying, slightly more deformed Tyler strata by a decollement, but a decollement has not been observed in the region. Hotchkiss (1919a, b) reported the presence of a bedding plane fault, with minimum eastward offset, near the base of the Ironwood Iron-formation in underground mines.

D_2 Event

Whereas D_1 deformed only Early Proterozoic strata, D_2 deformed both Early Proterozoic and Archean rocks. Structures attributed to D_2 occur in pelitic layers in the Early Proterozoic strata at Falls River, Little Mountain, Taylor mine, Canyon Falls, and the Ironwood-Hurley areas; and D_2 deformation occurs as a mylonitic fault zone at Plumbago Creek and possibly at Komtie Lake (table 2). Kinematic data from Archean gneiss at Plumbago Creek indicate that Archean rocks were thrust northward along the

Table 2. Summary of deformation observed at Falls River, Little Mountain, Taylor mine, Plumbago Creek, Komtie Lake, Canyon Falls, Covington profile, and Ironwood-Hurley area, Michigan and Wisconsin

Deformation D_1	Deformation D_2	Deformation D_3	Remarks
North-verging thrust system, which appears to have affected only Early Proterozoic strata. Its confinement to Early Proterozoic strata suggests that it was a thin-skinned deformational event.	North-verging thrusting colinear with deformation D_1. Involved both basement rocks and overlying Early Proterozoic strata.	Local high-angle thrusting toward east-northeast. Involved Archean basement and overlying strata.	
Structural elements: Bedding S_0 Fold axes F_1 Foliation or cleavage S_1 Stretch lineations L_S	Structural elements: Fold axes F_2 Foliation or cleavage S_2 Stretch lineations L_S	Structural elements: Local crinkle folds on S_1 F_3 Foliation or cleavage S_3 Fold axes in S_1 F_3	
Falls River: FR S_0, F_1, S_1	F_2, S_2	F_3, S_3, F_3	D_1 and D_2 structural elements prominent; D_3 occurs at isolated locations.
Little Mountain: LM S_0, F_1, S_1, L_S	F_2, S_2	?	D_1 and D_2 structural elements prominent; D_3 not observed.
Taylor mine: TM S_0, F_1, S_1, L_S	F_2, S_2	F_3	D_1 and D_2 structural elements prominent; evidence for D_3 weak.
Plumbago Creek: PC S_0, F_1, S_1	F_2, S_2	F_3, S_3	D_1, D_2, D_3 elements prominent; D_1 found only in Early Proterozoic rocks; D_3 occurs as localized shear zones.
Komtie Lake: KL S_0 ?	F_2	F_3, S_3, F_3	Data from unoriented drill core difficult to distinguish D_1 from D_2 from D_3. S_3 and F_3 definitely observed on surface.
Canyon Falls: CF S_0 ?	F_2, S_2, L_S	?	Massive quartzite, subhorizontal bedding. S_2 foliation in thin, intercalated pelitic layers.
Covington profile: CP S_0, F_1, S_1	F_2, S_2	?	D_1 structural elements prominent in roadcuts, south-dipping S_1 and upright F_1 folds.
Ironwood-Hurley: IH S_0, S_1	F_2, S_2	?	D_2 elements, especially F_2 and S_2, seen in broader area to south. Foliation (S) at Tyler outcrop is interpreted as S_1.

mylonitic fault zone. Thick-bedded quartzite, such as at Canyon Falls, was rigidly attached to the underlying Archean gneiss and was possibly folded during D_2. Such folding may have caused slip along bedding that induced S_2 foliation in thin pelitic layers and formed northerly oriented striations on bedding planes at Canyon Falls.

The D_2 deformation, which was coaxial with D_1 (that is, both F_1 and F_2 fold axes trend west-northwest), may have caused the overturning of bedding at the top of Little Mountain. This was accomplished by movement along bedding plane faults that overturned the north limbs of the earlier north-verging F_1 folds and also caused kink folding of S_1 foliation. Northeasterly oriented slickenlines on bedding planes and a northerly overturning of bedding indicate a northeasterly sense of vergence in the overturned folds at Little Mountain; also, some of the kink folds in S_1 along the Covington profile are interpreted to be D_2.

The D_2 deformation was thick skinned and involved Archean crystalline basement as well as Early Proterozoic rocks. This is most clearly seen at Plumbago Creek, where D_2 has formed mylonite zones in the Archean gneiss. Similar examples of post-D_1, thick-skinned structures are found elsewhere in the Marquette trough region. Klasner and Cannon (1974) showed that the contact along the south margin of the Marquette trough dips steeply south, coinciding with a high-angle reverse fault. Also, a high-angle reverse fault at a large angle to S_1 (see Cannon and Klasner, 1976) occurs along the west edge of the southern complex (fig. 1). This fault postdates D_1 and has been interpreted as D_2 in age. It demonstrates that the D_2 faults occur along the contact between Early Proterozoic rocks and Archean gneiss at various orientations relative to the consistently west-northwest-oriented S_1 foliation. The mylonitic fault zone along Plumbago Creek is interpreted to be a D_2 fault, but it dips less steeply (≈30°) than do some other reverse faults described previously.

The mylonite zones in the drill core at Komtie Lake may have formed due to D_2 deformation. Because the strike of the mylonitic foliation in the drill core is not known, the deformation could be either D_2 or D_3; D_3 foliation (S_3) and fold axes (F_3) have been observed in outcrops near Komtie Lake.

Geologic and geophysical data collected from areas south and east of the Tyler outcrop at Ironwood-Hurley suggest thick-skinned (D_2) deformation in this region also, similar to that found 150 km east near L'Anse. For example, structural studies in the Watersmeet area of northern Michigan (Sims and others, 1984), about 40–60 km east of the Ironwood-Hurley location, show that Early Proterozoic strata of the Menominee and Baraga Groups have been intensely deformed. A structural cross section by Sims and others (1984, fig. 3) suggests that the Archean Puritan batholith was also involved in the deformational event, but the exact nature of this deformation is not known. Recent studies by Cannon and others (1990) suggest that the south-dipping fold axes and axial-planar foliation were rotated clockwise some 30° to 60° during the Keweenawan rifting. If the crust in this area were rotated back to its pre-Keweenawan orientation, the folds and foliation in and adjacent to the south edge of the Puritan batholith would dip steeply south.

Gneiss domes in the Watersmeet area (Sims and Peterman, 1976) lie just south of the Puritan batholith. Attoh and Klasner (1989) suggested that anatectic remobilization of the gneiss, as proposed by Sims and Peterman (1976), was caused by tectonic stacking during the Penokean overthrust event. In this scenario, D_1 thin-skinned deformation deformed rocks that subsequently were eroded. Except for the Tyler strata to the north, the only evidence for D_2 is preserved at the deep tectonic level exposed in the region, particularly in the Watersmeet area where structures are largely upright. Structures north of Watersmeet would also be upright prior to their rotation during the Keweenawan rift event. In any case, the remobilized gneiss dome and associated upright Early Proterozoic structures in Archean rocks at Watersmeet and adjacent areas indicate unequivocally that deformation was thick skinned in that region.

D_3 Event

Although evidence for a third stage of deformation exists at several locations, the deformational features (folds and faults) are small, isolated, and poorly developed relative to D_2 and D_1 structural features. D_3 structures occur as north-northeast-trending faults in Archean rocks at Plumbago Creek and Komtie Lake and clearly deform earlier structures. Elsewhere evidence for D_3 comprises crenulation lineations on S_1 at Taylor mine and in the graphite pit at Plumbago Creek, some(?) of the kink bands along the Covington profile, and small isolated foliation and folds at Falls Creek. Because of their wide separation from each other, it cannot be unequivocally demonstrated that these structures are all genetically related.

Summary

The three stages of deformation identified in this study are interpreted as follows: D_1 represents thin-skinned shortening of Early Proterozoic strata along decollements that exist at low stratigraphic levels within the Early Proterozoic section. Deformation formed north-verging structures such as those at Falls River, Little Mountain, Taylor mine, and along the Covington profile. South-dipping foliation was also formed in the Early Proterozoic rocks at Plumbago Creek.

D_2 refolded already-deformed Proterozoic strata and the Archean basement rocks. D_2 was coaxial with D_1 in the areas of this study, but elsewhere in northern Michigan it was not. Intense anisotropy due to S_1 foliation in Early Proterozoic supracrustal rocks caused D_2 to behave in a brittle, kink-fold manner relative to D_1. The thrust fault at Plumbago Creek is interpreted as D_2. In the west, D_2 deformation may have produced gneiss domes in Archean rocks and upright folds in Proterozoic rocks along their contact with Archean basement.

D_3 represents late-stage faulting along localized zones. It caused weak deformation of preexisting (especially S_1) structures, such as at Plumbago Creek. Deformation may have resulted from late block uplift of Archean basement (Cannon and Klasner, 1972).

CONCLUSIONS AND TECTONIC IMPLICATIONS

A north-verging fold-thrust system in the Early Proterozoic continental foreland of the Superior craton in Minnesota, southern Ontario (Zolnai and others, 1984), and northern Michigan is well known. However, documentation of this deformation in Michigan has previously been confined to the eastern part of the exposed Penokean orogen in Michigan (Klasner, Sims, and others, 1988). In this report, we show that north-verging deformation also exists farther west, extending into northern Wisconsin. We have documented the nature and sequence of this deformation at two widely separated locations (L'Anse and Ironwood-Hurley) in northern Michigan and Wisconsin.

Previous workers have generally agreed that deformation of the Penokean continental foreland was caused by suturing of the Wisconsin magmatic terranes with the continental foreland along the Niagara fault at about 1,850 Ma. The exact relationship between the multiphase deformational sequence described in the preceding section and collision of the magmatic terranes with the continental foreland is unclear. Data presented herein suggest that some Early Proterozoic strata are allochthonous, that is, were transported along a sole thrust during D_1 deformation. However, Barovich and others (1989) have shown from Nd isotope studies that Early Proterozoic sediments in the northeastern part of the orogen, near L'Anse (north of Covington), were derived from Archean crust, whereas Early Proterozoic sediments farther south in the Penokean orogen were foreland deposits derived in large part from the Wisconsin magmatic terranes. Thus, Early Proterozoic strata in the northern exposures cannot have been tectonically transported from the vicinity of the Wisconsin magmatic terranes. Structural evidence indicates that they were transported northward, but only a short distance within the distal part of the foreland basin.

In the L'Anse area, D_2 deformation involved reverse faults similar to those along the south edge of the Marquette trough in northern Michigan. Similarly, in the Ironwood-Hurley area to the west, D_2 deformation involved dislocation of Archean basement. Thus, the extent of D_2 collision-related deformation is more extensive than previously thought. It now appears that D_2 is a continuum of collisional tectonics that started with an initial D_1 phase of thin-skinned deformation.

Attoh and Klasner (1989) suggested that vertical remobilization of Archean basement was caused by anatectic melting beneath tectonically stacked Early Proterozoic rocks. They showed that burial (metamorphic pressure) was deepest in the west (Watersmeet node), where evidence for anatectic remobilization is strong. In the northeast, depth of burial was much shallower. The stacked thrust-fold sheets are now eroded, but the Tyler Formation outcrop in the Ironwood-Hurley region, which was probably deformed during D_1, most likely represents a remnant of one of these thrust sheets. Erosion may have removed most shallow D_1 structures, leaving mostly D_2 structures exposed in the Watersmeet region.

Holst (1989) has documented two structural domains in east-central Minnesota, and has suggested that they extend into northern Michigan. The northern domain comprises one major period of deformation characterized by open to closed, upright folds with easterly trending subhorizontal fold axes and a single steep-dipping axial-planar foliation. These structures occur in the Animikie basin rocks of Minnesota and are correlated with the Covington profile, Little Mountain, and Falls Creek areas of northern Michigan. The southern domain, west and south of Duluth, Minn. (fig. 1), comprises nearly isoclinal recumbent folds, with subhorizontal easterly trending fold axes, and subhorizontal axial-planar foliation, which has been folded by a later D_2 event that formed steep upright foliation similar to that found in the northern domain. Holm and others (1988) proposed a possible tectonic model for the inferred deformational history involving imbricate northwesterly thrusting associated with oblique subduction to the southeast. Holst (1991) has suggested that the region south of Covington in the Horse Race Rapids, Felch, and Calumet troughs areas are structurally comparable to the southern domain of Minnesota.

Morey and Sims (1976) recognized a difference in structural style in the rocks of east-central Minnesota on opposite sides of the Archean Great Lakes tectonic zone (GLTZ). The GLTZ separates less complexly deformed rocks on the north from more complexly deformed rocks to the south. Sims and others (1980) extended the GLTZ into northern Michigan, as shown in figure 1.

The two structural domains of the Penokean orogen in Michigan, that is, the imbricate thrust belt and the foreland thrust belt, fit, in a general sense, the two structural domains described by Holst (1989). However, the upright structures of the foreland thrust belt found along the Covington profile occur south of the GLTZ (as presently located by Sims and others, 1980), suggesting either that the GLTZ was not a controlling factor in the structural evolution of the Penokean orogen in this area, or that the correlation of structural domains between Michigan and Minnesota is not valid in detail.

Barovich and others (1989) showed that Early Proterozoic sediments in the L'Anse area, north of the northern complex (fig. 1), have Archean model ages, whereas those along the Covington profile were derived from an Early Proterozoic terrane. Therefore, the sedimentary fill in the basins north of the northern complex was derived from exposed Archean rocks to the north and was multiply deformed (D_1, D_2, D_3) during Penokean deformation. The sedimentary rocks south of the northern complex, along the Covington profile, characterized by upright north-verging structures and a prominent south-dipping cleavage (S_1), were derived from a migrating tectonic front and deposited in a foreland basin such as that proposed by Hoffman (1987) and Southwick and Morey (in press) during the Penokean orogeny.

Studies such as those of Holst (1989), comparing the structures of the Penokean orogen from widely separated regions, should constitute the next step in determining the evolution of the foldbelt; we stress the need for further work of this nature from southern Ontario to northern Michigan and Wisconsin to Minnesota, along the whole length of the foldbelt. Likewise, further studies such as those of Cannon and others (1990) are needed to assess the effect of the Keweenawan rift event on earlier structures in the region.

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