Thick-Skinned, South-Verging Backthrusting in the Felch and Calumet Troughs Area of the Penokean Orogen, Northern Michigan

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Chapter L

Thick-Skinned, South-Verging Backthrusting in the Felch and Calumet Troughs Area of the Penokean Orogen, Northern Michigan

By J.S. KLASNER and P.K. SIMS

U.S. GEOLOGICAL SURVEY BULLETIN 1904

CONTRIBUTIONS TO PRECAMBRIAN GEOLOGY OF LAKE SUPERIOR REGION

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

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Thick-Skinned, South-Verging Backthrusting in the Felch and Calumet Troughs Area of the Penokean Orogen, Northern Michigan

By J.S. Klasner[1] *and* P.K. Sims

Abstract

The Felch and Calumet troughs area of northern Michigan is part of the Penokean fold-thrust belt of the continental foreland of the Superior craton. The area lies immediately north of the Niagara fault zone, the north-verging suture between the continental foreland and the Early Proterozoic Wisconsin magmatic terranes to the south. Accretion of the magmatic terranes to the continental margin ≈1,850 Ma produced south-verging backthrusting and backfolding in this region involving both Archean basement and Early Proterozoic supracrustal strata.

Evidence for backthrusting exists throughout the Felch and Calumet troughs area. The backthrusting is characterized by southward-overturned bedding and small-scale, south-verging asymmetric folds with a subhorizontal axial-planar foliation. The Carney Lake Archean block appears to be a crystalline-core nappe wherein the Sturgeon Quartzite of the Chocolay Group forms the lower overturned limb. The deformation probably started as a north-verging foreland thrust event, but out-of-sequence south-verging backthrusts and backfolds developed to accommodate abrupt changes in crustal thickness along the continental margin.

The backthrusting in the Penokean orogen resembles that in the younger rocks of the southern Alps. Proceeding inward from the continental margin, both orogens have accreted oceanic crust, indicated by the presence of ophiolite, that is thrust onto the continental margin; a zone of thick-skinned complex deformation characterized by backthrusting and backfolding; a marginal basement arch; and, inboard of the arch, a fold-thrust belt that mainly involves thin-skinned deformation.

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INTRODUCTION

Geologic mapping and related studies of the Precambrian rocks in northern Michigan, done mainly during and shortly after World War II, have provided excellent detailed geologic maps that can be reinterpreted in terms of modern structural analysis. In this study we have utilized the geologic maps of the area comprising the Felch and Calumet troughs (Gair and Wier, 1956; Bayley, 1959; James and others, 1961; Bayley and others, 1966; Dutton, 1971) to reinterpret the structural evolution. These maps show outcrops and numerous faults, most of which were interpreted originally as high-angle normal faults. Many of these faults are here reinterpreted as thrust and reverse faults.

In a recent structural study, Maharidge (1986) suggested that the Early Proterozoic stratigraphy in the Felch trough is inverted and possibly represents the lower limb of a crystalline, basement-cored nappe. (See also Sims and others, 1987.) Maharidge pointed out that the rocks in this area have been subjected to at least two phases of deformation. The first phase produced a north-verging crystalline-cored nappe with subhorizontal foliation; the second phase produced upright folds having a steeply dipping foliation. Holst (1982, 1984) has suggested that similar north-verging nappes exist in the Early Proterozoic continental foreland in east-central Minnesota.

In this report we point out that although the Bush Lake fault is a major north-verging structure, consistent with the overall sense of northward tectonic transport of the Penokean orogen in northern Michigan and adjacent Wisconsin (Sims and others, 1985; Klasner, Ojakangas, and others, 1988; Klasner, Sims, and others, 1988; Attoh and Klasner, 1989; Klasner and Cannon, 1989; and Klasner and others, 1991), the structures in the Felch and Calumet troughs area are south-verging (Klasner and Sims, 1989). The south-verging structures, which deform Archean basement as well as rocks of the Early Proterozoic Marquette Range Supergroup, are interpreted as out-of-sequence backthrusts and backfolds that developed to accommodate abrupt changes in crustal thickness along the continental margin caused by thrusting. Our study did not confirm the existence of an inverted Early Proterozoic stratigraphy throughout the area of the Felch and Calumet troughs.

The structural analysis presented in this report differs substantially from the earlier conclusions of Ueng and Larue (1988) for the same general area. They recognized local flat foliations but related them to vertical compression rather than thrusting.

ACKNOWLEDGMENTS

We thank several colleagues for their kind help. James Trow provided structural data from the Calumet trough, and D.K. Larue and J.J. Mancuso provided information on the Groveland iron mine. Discussions in the field with W.F. Cannon, Z.E. Peterman, and K.J. Schulz provided considerable insight to this study, but we remain responsible for the interpretations set forth in this report. F.W. Cambray and R.L. Bauer reviewed final versions of the manuscript.

REGIONAL TECTONIC SETTING

The Felch and Calumet troughs lie near the south edge of the exposed continental margin of the Archean Superior craton (figs. 1 and 2). Rocks of the Wisconsin magmatic terranes (Sims and others, 1989) were accreted to the continental margin along the north-verging Niagara fault (suture) zone at about 1,850 Ma, resulting in northward thrusting and development of prominent thrust-fold systems (Klasner, Sims, and others, 1988) on the continental foreland. The Niagara fault zone contains a dismembered ophiolite comprising LREE (light-rare-earth-element)-depleted basalt, sheeted dikes, serpentinite, and plagiorhyolite (Schulz, 1987; Sims and others, 1989). In Minnesota, Holst (1984) and Southwick and Morey (1991) have described large-scale nappes and thrusts that presumably are related to the same collision.

The Penokean orogen in northern Michigan has been divided into two major structural domains (Klasner and Cannon, 1989; Klasner, Ojakangas, and others, 1988; Klasner, Sims, and others, 1988). The northern domain, in the northern part of the Baraga basin (fig. 1), consists of a foreland-basin thrust belt in which deformation was largely thin skinned (Klasner and others, 1991); that is, it involved mainly Early Proterozoic supracrustal rocks, with apparently minor deformation of Archean basement rocks. The southern domain, which includes the study area and the Archean outliers in the Baraga basin just north of the study area, consists of a basement arch in which deformation was primarily thick skinned, that is, it involved both Early Proterozoic supracrustal rocks and Archean basement. The Felch and Calumet troughs area is in the southern domain.

BEDROCK GEOLOGY

The Felch and Calumet troughs (fig. 2) are elongate east-trending belts of Early Proterozoic sedimentary and minor volcanic rocks that unconformably overlie or are in fault contact with Archean basement rocks. The Early Proterozoic rocks in the area are assigned to the Marquette Range Supergroup, which has been divided into four groups (Cannon and Gair, 1970), from youngest to oldest, the Paint River, Baraga, Menominee, and Chocolay. The youngest recognized group, the Paint River, lies mostly to the west of the area of figure 2, and is not considered in this study. Sims (1992) has suggested that the Paint River Group probably is not a valid group, but instead contains rocks correlative with the Michigamme Formation of the Baraga Group. The Baraga Group consists mainly of graywacke and slate of the Michigamme Formation. Within the area of figure 2, the Menominee Group comprises the Vulcan Iron-formation and the underlying schistose rocks of the Felch Formation (combined as unit Xme) and two major volcanic units, the Badwater Greenstone and the Hemlock Formation. Chemical data (K.J. Schulz, oral commun., 1990) indicate that the Badwater and Hemlock are probably correlative. The Chocolay Group consists of the Randville Dolomite, the underlying Sturgeon Quartzite, and the basal Fern Creek Formation (not divided in fig. 2). The Fern Creek is exposed only locally, and the Sturgeon Quartzite generally is the lowermost Early Proterozoic unit (Bayley and others, 1966).

The study area, which we call the Felch and Calumet troughs area, consists of several fault-bounded domains (fig. 2), each of which has different rock units and structure. The Amasa block, to the north, is bounded on the south by the Bush Lake fault; it consists of Archean gneiss and the overlying Hemlock and Michigamme Formations, which have a northwest structural grain. The north-central part of the study area (fig. 2) contains several east-trending troughs of supracrustal rocks that are separated from Archean gneiss blocks by faults. From north to south, these domains are the Bush Lake trough, the Dickinson Group block of Archean gneiss and supracrustal metaconglomerate, the Felch trough, the South Felch Archean block, the Toby Lake Archean block, the Calumet trough and its westward extension into the Horserace Rapids area (fig. 2), and the Carney Lake Archean block. The Crystal Falls and Florence-Niagara terranes (Sedlock and Larue, 1985; Ueng and Larue, 1988), labeled in figure 2 for completeness and context, are not considered further in this study.

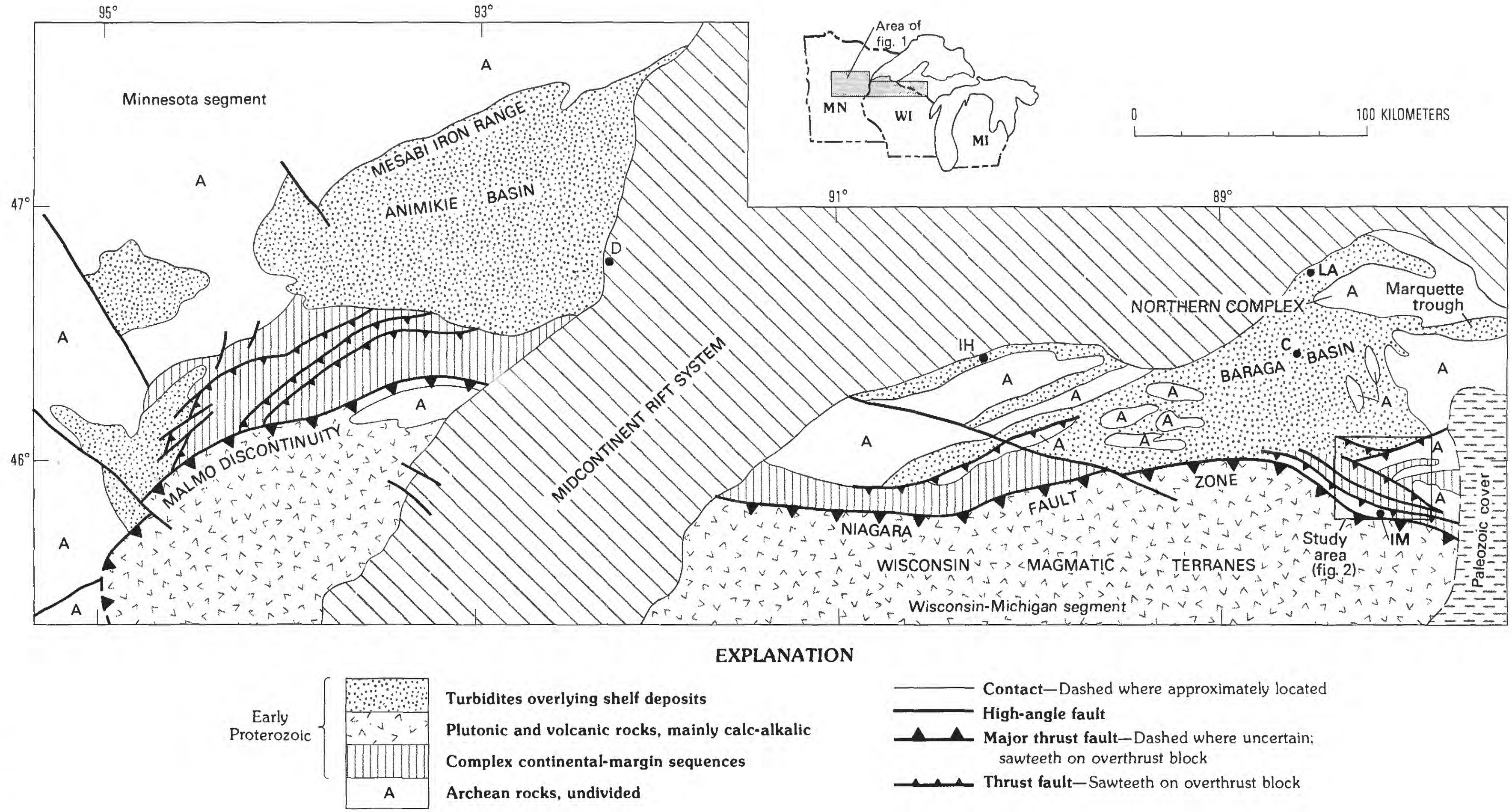
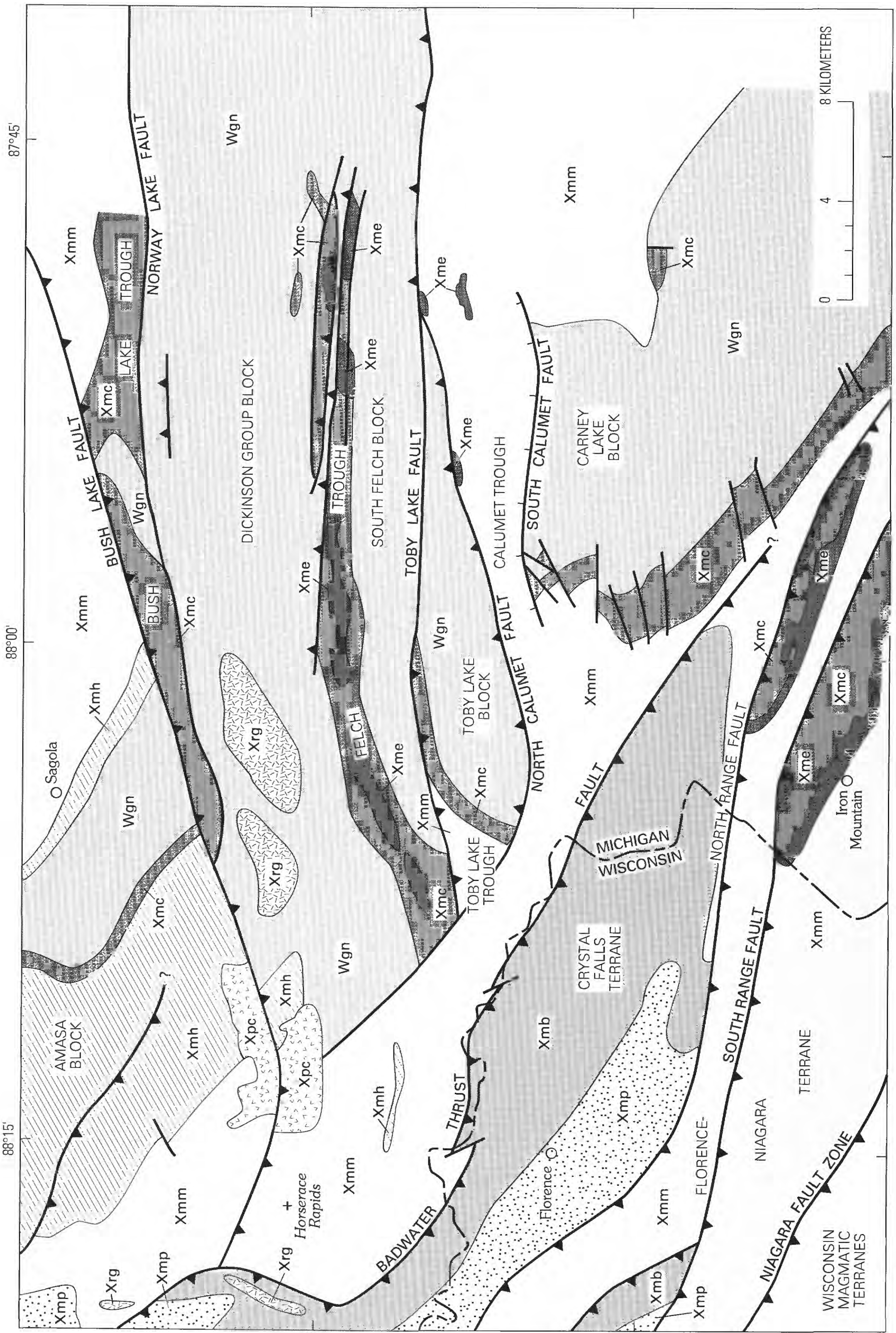


Figure 1. Map of northern Michigan-Wisconsin and Minnesota segments of the Penokean orogen, divided by rocks of the Midcontinent rift system (modified from Holst, 1991). Towns shown for reference include L'Anse, Mich. (LA), Covington, Mich. (C), Iron Mountain, Mich. (IM), Ironwood-Hurley, Mich. and Wis. respectively (IH), and Duluth, Minn. (D).



87°45'
88°00'
88°15'
46°00'
45°45'
NORWAY LAKE FAULT
BUSH LAKE FAULT
BUSH LAKE TROUGH
DICKINSON GROUP BLOCK
FELCH TROUGH
SOUTH FELCH BLOCK
TOBY LAKE FAULT
TOBY LAKE BLOCK
TOBY LAKE TROUGH
CALUMET TROUGH
SOUTH CALUMET FAULT
NORTH CALUMET FAULT
CARNEY LAKE BLOCK
AMASA BLOCK
BADWATER THRUST FAULT
CRYSTAL FALLS TERRANE
MICHIGAN
WISCONSIN
NORTH RANGE FAULT
SOUTH RANGE FAULT
FLORENCE-NIAGARA TERRANE
NIAGARA FAULT ZONE
WISCONSIN MAGMATIC TERRANES
Sagola
Horserace Rapids
Florence
Iron Mountain
Xmm
Wgn
Xmc
Xme
Xmh
Xrg
Xpc
Xmb
Xmp
0
4
8 KILOMETERS

REGIONAL STRUCTURE AND METAMORPHISM

The Early Proterozoic and Archean rocks in the area were subjected to multiple deformations (table 1). These deformational phases (D_1, D_2, D_3) are unequivocally Early Proterozoic in age because they deform Early Proterozoic rocks, and they predate the ≈1,824 Ma post-tectonic granite pluton (Klasner, Ojakangas, and others, 1988; unit Xrg, this report) that intrudes deformed Michigamme slate in the northwest corner of the map area (fig. 2).

The initial phase of Early Proterozoic deformation (D_1) produced a penetrative, subhorizontal to steeply dipping foliation (S_1) in most of the Early Proterozoic rocks and a penetrative foliation in much of the Archean crystalline rocks. The foliation is expressed by aligned biotite, sericite, and chlorite in the Proterozoic rocks and by aligned biotite and muscovite, which together crosscut an older steep gneissic banding in the Archean rocks. Foliation S_1 is axial-planar to D_1 folds that have gently plunging F_1 fold axes; D_2 is characterized by a spaced, but locally a penetrative, foliation (S_2) in both Early Proterozoic and Archean rocks. At places S_2 is axial-planar to observed crenulation folds in S_1. D_3 deformation is recognized at a few localities as crenulation folds that affect both S_1 and S_2; a late phase of dextral faulting may correlate with D_3. These late deformational phases were not studied in detail.

EXPLANATION

EARLY PROTEROZOIC (1,600-2,500 Ma)

Xrg	Red granite
Xpc	Peavy Pond Complex
	Marquette Range Supergroup
Xmp	Paint River Group
Xmm	Michigamme Formation of Baraga Group
	Menominee Group
Xme	Sedimentary rocks
Xmh	Hemlock Formation
Xmb	Badwater Greenstone
Xmc	Chocolay Group

ARCHEAN (2,500 Ma and older)

Wgn	Gneiss and metaconglomerate

Contact

Fault—Sense of movement uncertain

Normal fault—Hachures on downthrown side

Thrust fault—Sawteeth on upper plate; queried where extent uncertain

Figure 2 (above and facing page). General geology of the Felch and Calumet troughs area. Modified from Sims (1990), Cannon (1986), and James and others (1961).

Table 1. Explanation of alphanumeric symbols used to describe deformation events and structural features in the Felch and Calumet troughs area

Early Proterozoic:	
D_1	Deformational event that formed S_1 foliation, which is axial-planar to D_1 folds (F_1). L_1 lineations formed by intersection of S_1 foliation and S_0 bedding. L_s, stretch lineations formed during F_1 deformation.
D_2	Second deformational event, which formed S_2 foliation; S_2 is axial-planar to D_2 folds (F_2). L_2 lineations are caused by intersection of S_1 and S_2.
D_3	A third deformation event, which formed rare crenulation fold lineations (F_3) on S_1 or S_2 foliation surfaces.
Archean:	
D_A	Multiple and complex deformation that occurred during Archean time.
S_A	Archean gneissic foliation.
L_A	Archean stretch lineation.

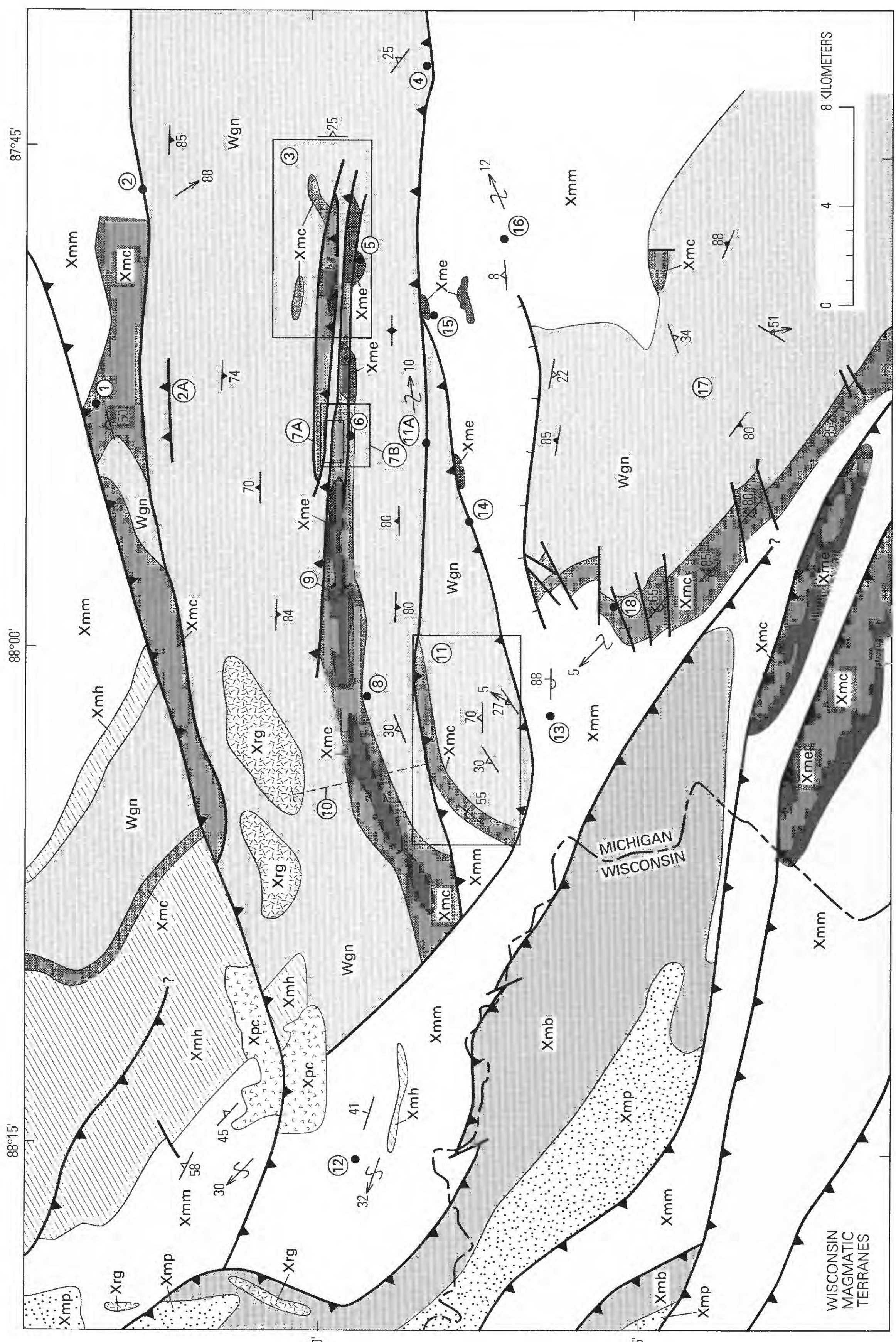
The dominant Archean structure in the area is a gneissic foliation (S_A) that dips steeply and is associated with steeply plunging fold axes (F_A) or stretch lineations (L_A). The Archean foliation generally strikes east to northeast, except in the Carney Lake block, where it strikes northwest.

The Peavy Pond Complex (fig. 2, unit Xpc) is the locus of high-temperature–high-pressure metamorphism (Attoh and Vander Meulen, 1984). Klasner (1972) and Bayley (1959) showed that the metamorphism mostly postdates D_1 deformation, and Klasner (1978) showed that metamorphism peaked during D_2 deformation. Through combined metamorphic, structural, and gravity modeling studies, Attoh and Klasner (1989) suggested that the high-grade metamorphism was caused by tectonic stacking during thrusting in the Penokean orogen.

KINEMATIC DATA IN THE STRUCTURAL DOMAINS

In this section, we present kinematic data from specific locations that show the sense of movement in each of the structural domains. Features such as asymmetry of folds, fold and stratigraphic facing, stretch lineations, and regional structural relations informed the kinematic analyses.

The features most useful for determining the sense of tectonic transport are facing directions and the vergence of minor folds. Facing refers to the direction of stratigraphic younging, which is determined from sedimentary structures, in a succession of beds or in a fold (Schackleton, 1957; Bell, 1981). Vergence of asymmetric folds has been defined (Roberts, 1974, p. 123) as "the horizontal direction, within the plane of the fold profile (perpendicular to fold axis), towards which the upper component of * * * rotation is directed." Also, sense of rotation of cleavage to bedding can define sense


87°45'
88°00'
88°15'
46°00'
45°45'
0
4
8 KILOMETERS
MICHIGAN
WISCONSIN
WISCONSIN MAGMATIC TERRANES
Xmm
Xmc
Xme
Xmh
Xrg
Xpc
Xmb
Xmp
Wgn

of vergence (Bell, 1981, p. 200). It is important to use both vergence, as determined from minor structures, and facing together wherever possible. For example, facing and vergence must be used together to define which limb of a major fold one is working on, and in which direction the hinge of the fold is located.

Bush Lake Trough

The Bush Lake trough is bounded on the north by the Bush Lake fault and on the south by the Norway Lake fault (fig. 2). The Bush Lake fault is a classic example of a thrust fault; it truncates structures in the footwall whereas structures in the hanging wall are parallel to the thrust. It separates the Amasa block on the north from the Bush Lake trough on the south. Attoh and Vander Meulen (1984) have shown from metamorphic studies in the area of the Peavey Pond Complex that the southern block is upthrown. Their reconstruction of the geometry of metamorphic isograds suggests that the Bush Lake fault dips toward the south, but definitive data on the dip of the fault are not available.

Bedrock is poorly exposed in the Bush Lake trough. Most outcrops in the trough consist of the Randville Dolomite. One such outcrop, which lies approximately 260 m south of the trace of the Bush Lake fault (fig. 3, locality 1), exposes a contact between dolomite and a sandy dolomitic layer. A scour channel in the dolomite and inclusions of dolomite in the sandy layer indicate that bedding is overturned toward the north and dips steeply south (fig. 4*A*). Foliation (S_1) strikes northwest and dips gently southwest (fig. 4*B*). Cleavage-bedding relationships indicate that an overturned anticline exists to the north. Clearly, rocks in the hanging wall of the Bush Lake fault were subjected to northward-verging deformation.

Dickinson Group, South Felch, and Toby Lake Blocks

The Norway Lake fault separates the Dickinson Group block from the Bush Lake trough (fig. 2). A regional Archean fabric in gneisses just south of the fault (fig. 3, locality 2) consists of an east-trending, steeply dipping foliation (S_A). Deformed pebbles in the Archean gneiss have axes that plunge steeply southeast. In contrast, mylonitic and cataclastic structures within the Norway Lake fault zone overprint the regional Archean fabric, and therefore are presumed to be Proterozoic in age.

Several private-company drill holes penetrated a fault (fig. 3, locality 2A) 1 km south of the Norway Lake fault that definitely is a southward-verging thrust. The fault dips 45° N. and is marked by several centimeters of mylonite. Hanging-wall gneisses are intensely brecciated and chloritized.

The Dickinson Group block and the South Felch block are not continuous; they are separated by the Felch trough. However, during our study we recognized for the first time the existence of a pervasive, subhorizontal foliation that overprints the steep Archean gneissic fabric in both these blocks. The flat foliation (S_1), primarily aligned biotite, occurs in the Archean rocks adjacent to the Felch trough (fig. 3, area 3) and crosscuts the consistently steeply dipping Archean gneissic foliation (S_A) (fig. 5*A*, *B*). The flat foliation also crosscuts the Early Proterozoic strata of the Felch trough, as discussed following. Thus, it postdates deposition of the Early Proterozoic strata.

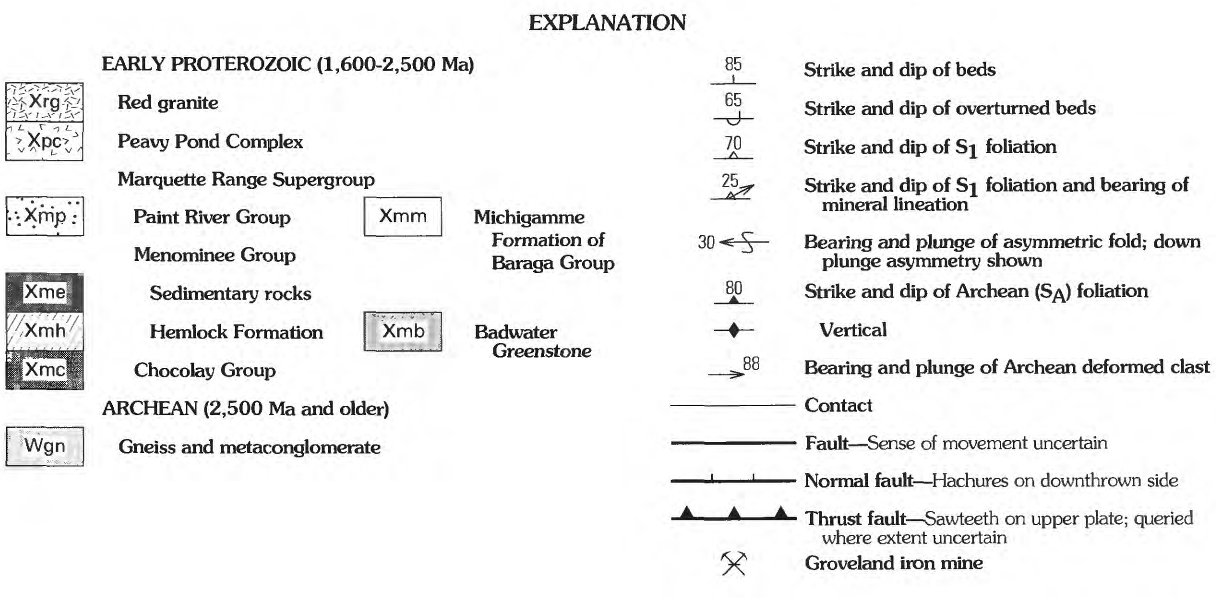


Figure 3 (above and facing page). Felch and Calumet troughs area, showing detailed rock attitudes and location of detailed study areas (circled numbers) discussed in text.

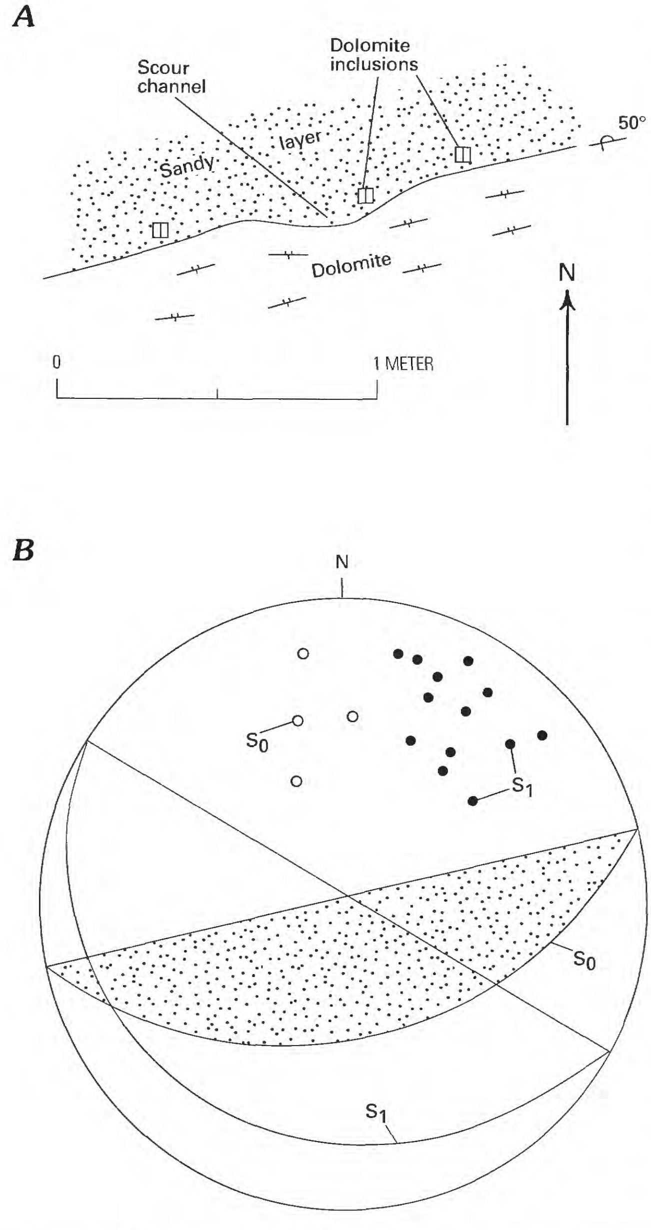


Figure 4. Outcrop near Bush Lake fault (fig. 3, locality 1). *A*, Field sketch; note overturned bedding. *B*, Lower hemisphere stereoplot; open circle, pole to bedding (S_0); solid dot, S_1 foliation. Average bedding plane (stippled) and S_1 foliation plane also shown.

The structural relationships among the relatively low dipping foliation (S_1), the steep Archean gneissic foliation (S_A), and a younger, steeply dipping foliation (S_2) in the Archean rocks within the South Felch block are illustrated in figure 6 (fig. 3, locality 4). The gneissic foliation (S_A) has been deformed into a southwest-verging minor fold with an axial-planar S_1 foliation. S_1, and presumably also S_A, although not directly observed, are deformed into small crenulation folds having a steeply dipping axial-planar foliation (S_2). S_1 foliation is oriented approximately N. 40° W., 25° NE., and S_2 is oriented generally N. 40° W., 50° NE. The asymmetric minor fold and S_1 foliation in Archean gneiss suggest south-verging deformation, consistent with senses of vergence elsewhere in the area, but stratigraphic facing directions are not known at this location.

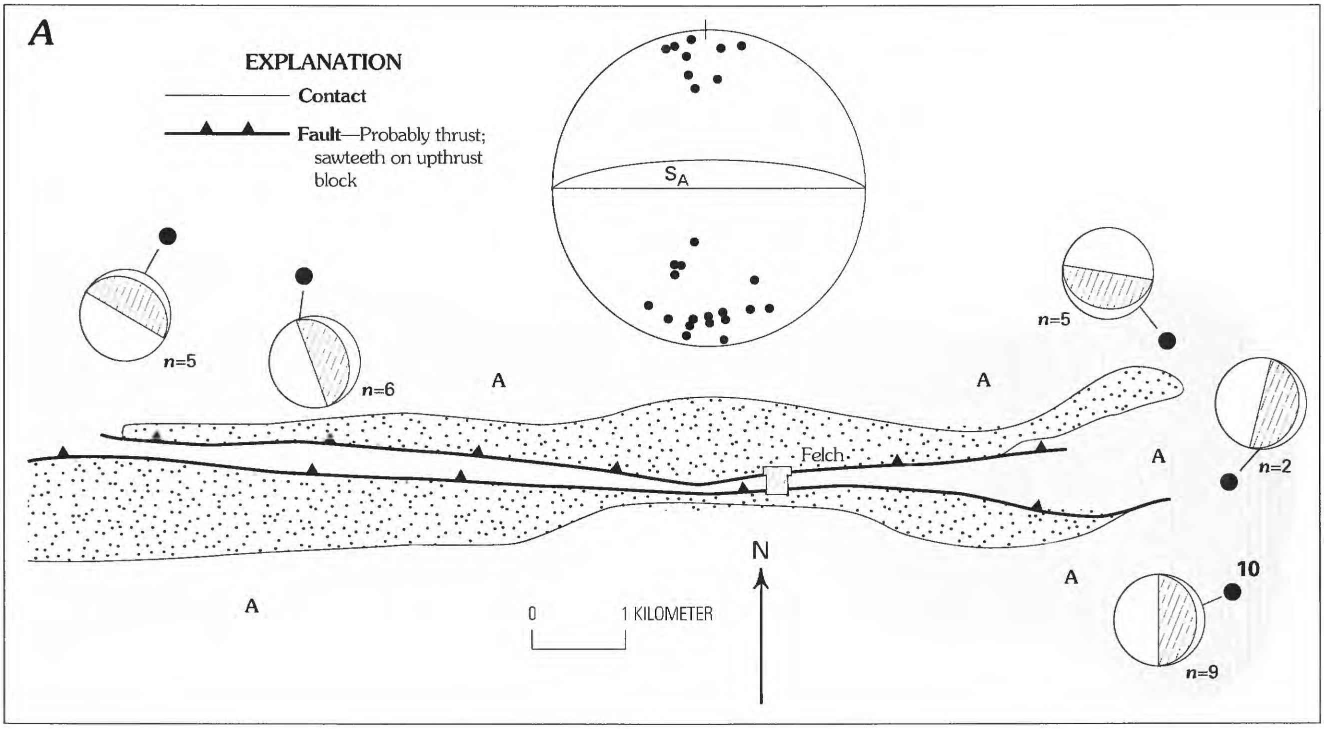
The Toby Lake block is bounded to the north by a north-verging thrust, the Toby Lake fault, and to the south by the south-verging North Calumet fault (figs. 2 and 3). The North Calumet fault truncates the Toby Lake fault to the east. The dominantly steep foliation (S_A) in the gneiss is deformed at places by S_1 foliation. S_1 foliation is best developed adjacent to the North Calumet fault, where it typically is a shallowly dipping mylonitic foliation. Mylonite is especially conspicuous in a post-tectonic (Archean) granite body in the southwestern part of the block. The foliation dips gently (25° –30°) north, and probably reflects a shallow northward dip of the North Calumet (thrust) fault.

Felch Trough

Rian quarry, which lies on the south edge of the Felch trough (fig. 3, locality 5), exposes a ≈40-m-long and ≈7-m-high quarry face of Randville Dolomite (Chocolay Group of Marquette Range Supergroup). Several features in the quarry face, diagrammatically sketched in figure 7*A*, show that the rocks here have been rotated toward the south. Bedding is vague in the dolomite, but where it can be recognized it is deformed into south-verging minor folds, as shown at points A, B, and C. A red sandy conglomeratic unit between points E and F is nearly vertical. Clasts of the red sandy layer in overlying dolomite (near point F) indicate that stratigraphic facing is to the south. A stereoplot (fig. 7*B*) indicates that bedding dips steeply, subparallel to the sandy layer. Foliation (S_1) dips moderately toward the north, as shown at point D. Bedding-cleavage intersection lineations (L_1) plunge gently southeast. Several small concretions in the dolomite near point E (fig. 7*A*) have long (stretch) axes that plunge steeply north-northeast. All structural data in the quarry indicate southward structural vergence.

A geologic map of the Felch trough near the Rian quarry (fig. 8; modified from James and others, 1961) shows that the Sturgeon Quartzite of the Chocolay Group crops out south of the quarry, suggesting (as shown in cross section of fig. 8) that a fault exists between the dolomite in the quarry and the quartzite. Such fault complications are supported by the presence of a roughly 5-m-wide slice of gneiss within the dolomite of the quarry. Presumably the gneiss is Archean and was tectonically emplaced from the underlying Archean basement.

Cross section *A–A′* (fig. 8) shows that the Felch trough in the area is south verging; it has a southward-overturned north limb and a gently north dipping south limb. Inasmuch as bedding dips more steeply than foliation in Rian quarry (fig. 7*A*, *B*), the quarry is located on the steep limb of a small



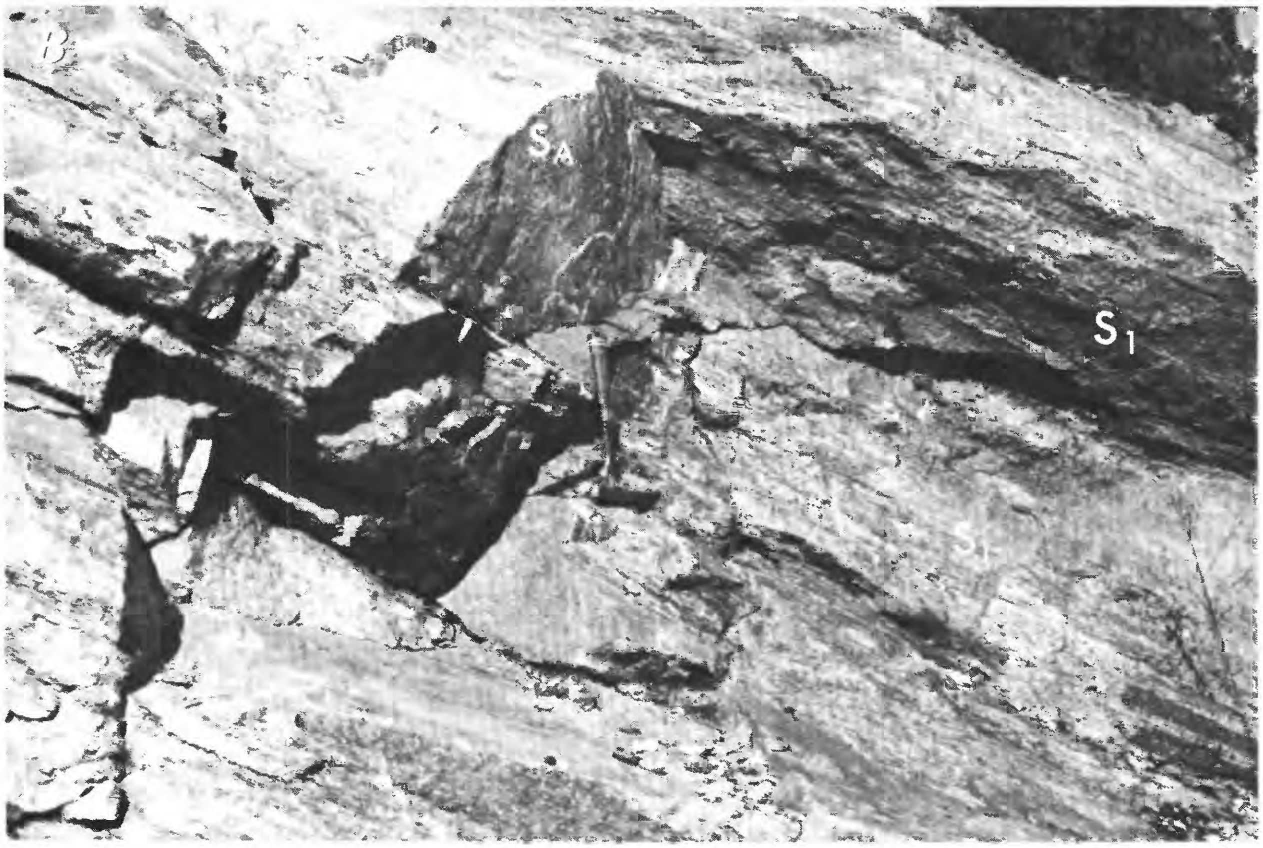


Figure 5. East end of Early Proterozoic Felch trough and adjacent Archean (A) rocks. *A*, Map of Felch trough (stippled), showing lower hemisphere stereoplots of poles to steeply dipping Archean gneissic foliation (S_A) and smaller lower hemisphere stereoplots of planes of S_1 foliation. Solid dots are localities (*n*=number of measurements) where S_1 was measured in Archean rocks (fig. 3, locality 3). Modified from Klasner, Sims, and others (1988). *B*, Outcrop 10 (in *A*), showing steeply dipping Archean foliation (S_A) and superimposed gently dipping Early Proterozoic foliation (S_1). Outcrop in roadcut on Dickinson County Highway 569. Hammer is 30 cm long.

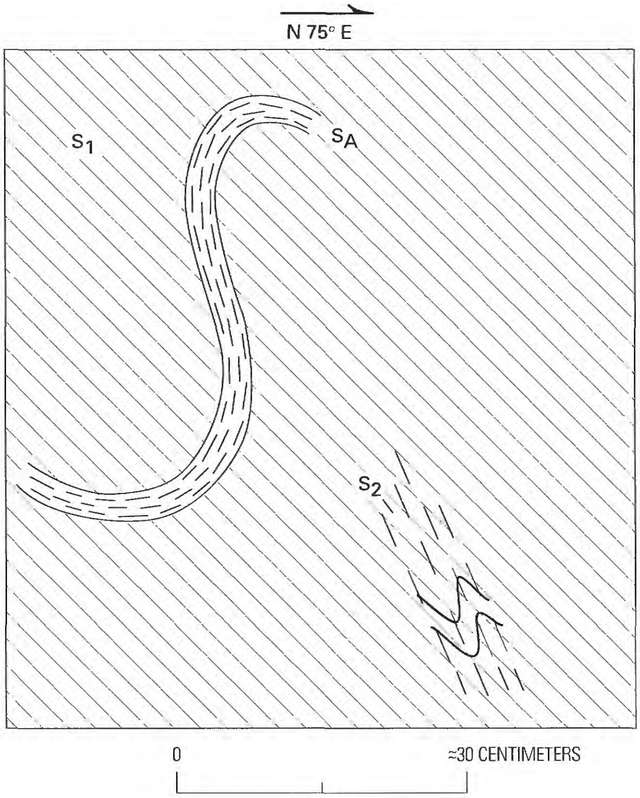


Figure 6. Field sketch showing D_1 folding of Archean foliation (S_A) and D_2 folding of S_1 foliation, in the South Felch block. S_2 is axial-planar to F_2 folds in S_1. Note that folding is south verging (fig. 3, locality 4).

parasitic fold such as that diagrammatically shown in figure 8. Like the minor folds observed on the cliff face of the quarry, the trough is most likely a parasitic fold on a much larger, but now largely eroded, south-verging fold system. The commonality between small-scale and large-scale structures is shown by the fact that the S_1 foliation is axial-planar to both the small folds at Rian quarry and the much larger synclinal fold of the Felch trough itself, which is an upward-facing fold.

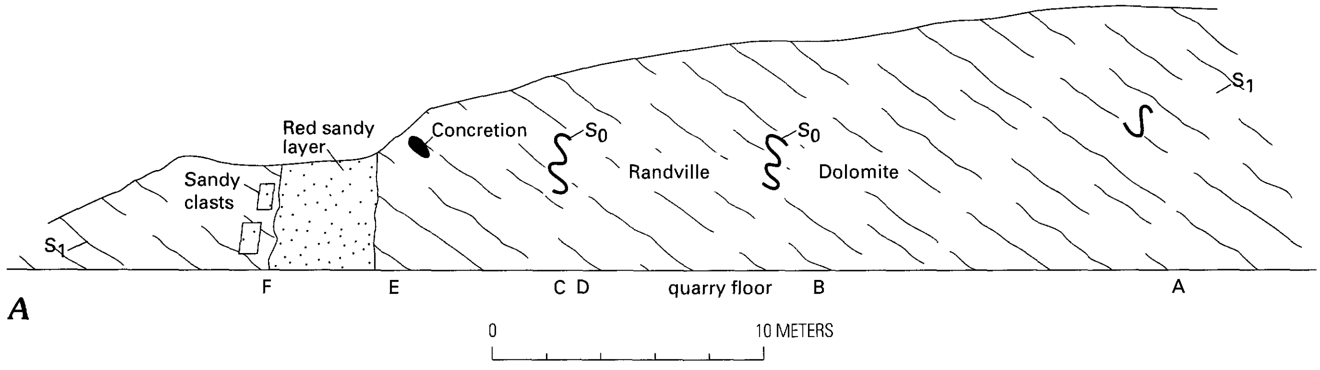
A hilltop outcrop of Sturgeon Quartzite at locality 6 in figure 3 reveals small scour channels and crossbeds, indicating stratigraphic tops to the south, and minor folds (fig. 9*A*). Bedding dips north and is overturned toward the south. A stereoplot (fig. 9*B*) shows that bedding has been folded about east-northeast-trending axes, as indicated by L and by the fold axis as determined from the pi diagram. Planar fabrics are poorly preserved in the massive quartzite and are difficult to measure. We are uncertain of the relative age of the foliation and have designated it as S without a subscript on figure 9*B*. Intersection of bedding (S_0) (not shown in fig. 9*B*) and S produces intersection lineations (L). The foliation (S), intersection lineations (L), and fold axes π_f, as determined from the pi diagram, may reflect D_2 deformation; a steep foliation is characteristic of S_2 elsewhere (see fig. 6). We interpret the southward-overturned bedding to represent the steep south limb of a minor fold, similar to that at Rian quarry.

A small area (fig. 10*A*) containing outcrops of Randville Dolomite, Sturgeon Quartzite, and Archean gneiss (fig. 3, area 7A) lies on the north limb of the Felch trough and provides data on structural vergence, the relationship between S_1 and S_2 foliation, and the sense of movement on a fault within the Felch trough. The outcrops depicted in figure 10*A* show a south-facing, inverted stratigraphy, that is, Sturgeon Quartzite on the north overlies steeply north dipping Randville Dolomite on the south. A parasitic fold is present in the dolomite (fig. 10*A*). Archean foliation (S_A) dips steeply, but it is overprinted and crosscut by a more gently dipping Early Proterozoic foliation (S_1). A shear zone occurs in the Randville Dolomite (near the road intersection in the northeast corner of area shown in fig. 10*A*). Quartz rods in the shear zone, which are considered to be a D_1 feature, plunge 30° NE.; and slickenlines also plunge northeast. The quartz rods and slickenlines give the direction of tectonic transport in the shear zone and, together with nearby drag folds and sense of rotation of Early Proterozoic strata, indicate a southwest sense of vergence.

Figure 10*B* provides a view of the stratigraphic and structural relationships in a larger area than figure 10*A* in this part of the Felch trough. The minor fold shown in the southwest corner of the figure area has been projected along strike onto the figure to show the sense of vergence on the south side of the Felch trough. The minor fold actually occurs to the west (fig. 3, locality 8). The hilltop exposure of Sturgeon Quartzite at locality 6 (fig. 3), which lies within the map area of figure 10*B*, is also shown in cross section *B–B′*.

The nature of the southward tectonic transport in the area is shown on interpretive cross sections *A–A′* and *B–B′* of figure 10. Section *A–A′* suggests that a south-verging thrust fault of Archean basement emplaced over the Proterozoic rocks caused southward overturning of the Early Proterozoic strata, as illustrated in section *B–B′*. The Felch trough at this location is a syncline overturned toward the south. The layer of Archean gneiss (Wg) in the center of the Felch trough (fig. 10 *A* and section *A–A′*) is interpreted as a klippe, that is, an allochthonous slice of gneiss emplaced above Early Proterozoic strata along the fault. Low-dipping S_1 foliation was formed during the D_1 phase of south-verging deformation. The hilltop exposure (fig. 3, locality 6) of southward-overturned strata of Sturgeon Quartzite remains as an erosional remnant in this south-verging thrust-fold system. We interpret the undulating nature of the south-verging thrust fault to be caused by D_2 deformation.

Ueng and Larue (1988) drew a structural cross section of the Groveland iron mine, within the Felch trough (fig. 3, locality 9), which we have modified herein (fig. 11). The section shows subhorizontal thrust faults that were deformed



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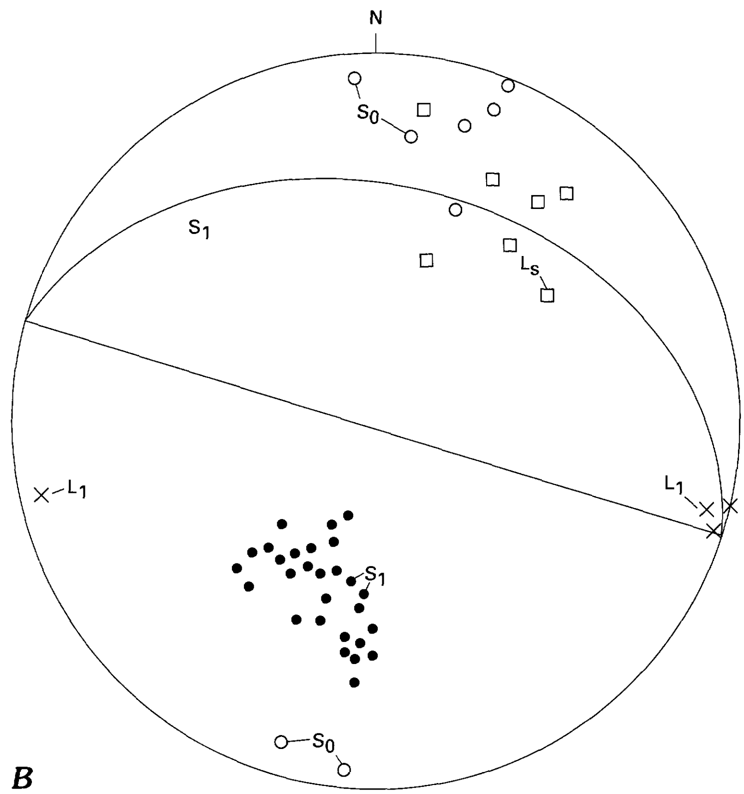


B

Figure 7. West cliff face of Rian quarry, Felch trough. *A*, Diagrammatic sketch. Cliff face is oriented N. 75° E., and composed of coarsely crystalline phase of Randville Dolomite. Red sandy layer occurs near south end. S_0, bedding; S_1, foliation (fig. 3, locality 5). Points A–F are described in text. *B*, Lower hemisphere stereoplot of structural features at Rian quarry. Open circle, pole to bedding (S_0); solid dot, pole to S_1 foliation; X, F_1 fold axis or L_1 lineation formed by intersection of S_0 and S_1; square, long stretch axis (L_S) of concretion. Note orientation of S_1 foliation plane.

by a later event. Ueng and Larue did not carry out kinematic analyses (D.K. Larue, written commun., 1988), but they diagrammatically showed south-verging minor folds in the Sturgeon Quartzite below the uppermost thrust fault. J.J. Mancuso (written commun., 1988), who also has done extensive work in the Groveland mine, recognized several low-dipping structures, but he observed numerous steeply dipping faults as well. Although we did not have access to the open-pit mine because of flooding and dangerous conditions, the data from Ueng and Larue (fig. 11) and Mancuso support the concept of a subhorizontal thrust event followed by a later, more steeply oriented deformation. In fact, Ueng and Larue (1988) pointed out that the low-dipping thrust surfaces, which we designate S_1, were significantly folded during a later event.

A gravity profile (fig. 12*A*) across the Felch trough, near its west end (fig. 3, locality 10), provides additional information on the structure of the trough. Observed gravity along the profile varies only slightly from the gently south dipping regional gravity gradient in the region. (See Klasner and others, 1985, for data on regional gradient.) The Early Proterozoic Felch trough has little gravity expression. The

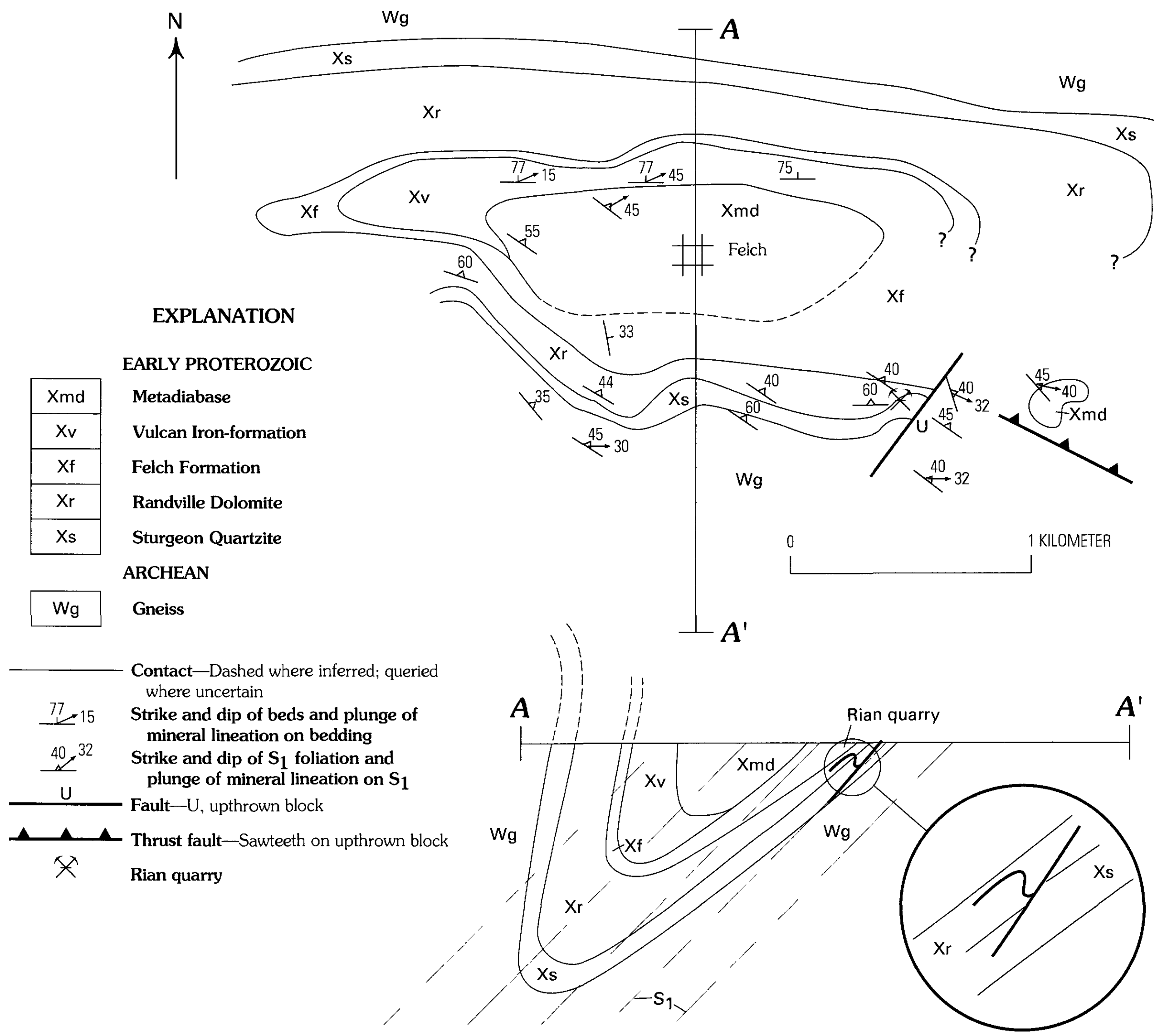


Figure 8. Felch trough in area of Rian quarry. Modified from James and others (1961) with additions by P.K. Sims. Quarry lies near south edge of trough. Cross section *A–A′* suggests that the southward-rotated Randville Dolomite strata at Rian quarry (fig. 7) are part of a drag fold and are separated from Sturgeon Quartzite on the south by a fault. S_1 foliation is axial-planar to folds in bedding at Rian quarry as well as to synclinally folded strata of Felch trough.

south half of the post-kinematic red granite pluton has a 3 milligal gravity low above it. An interpretive cross section (fig. 12*B*), constructed along the gravity profile, is based on correlation of the gravity profile with the bedrock geology mapped by James and others (1961) and on our structural measurements.

The gravity survey was designed to determine whether or not the stratigraphy is inverted in the Felch trough, but it yielded no evidence that the Early Proterozoic strata in this part of the trough are inverted (overturned). If the Early Proterozoic strata were overturned to form an antiformal syncline, as suggested by Maharidge (1986), a substantial body of buried Vulcan Iron-formation should have shown up clearly on the gravity survey. The structural data, which constrain fold symmetry, combined with the gravity data suggest that (1) the trough at this location is upward facing and asymmetrically inclined toward the south; (2) the steeply dipping north limb is slightly overturned toward the south and the south limb dips moderately toward the north; and (3) the axial plane of the trough dips about 50° N. The latter figure coincides with the earlier interpretation of James and others (1961) and is consistent with the relatively moderate dipping S_1 foliation found throughout the region, which is axial-planar to minor folds in the trough.

In summary, all the structural data observed along the length of the Felch trough indicate southward vergence. Evidence for a south-verging deformational event (D_1) is most notable in the central and eastern parts of the trough.

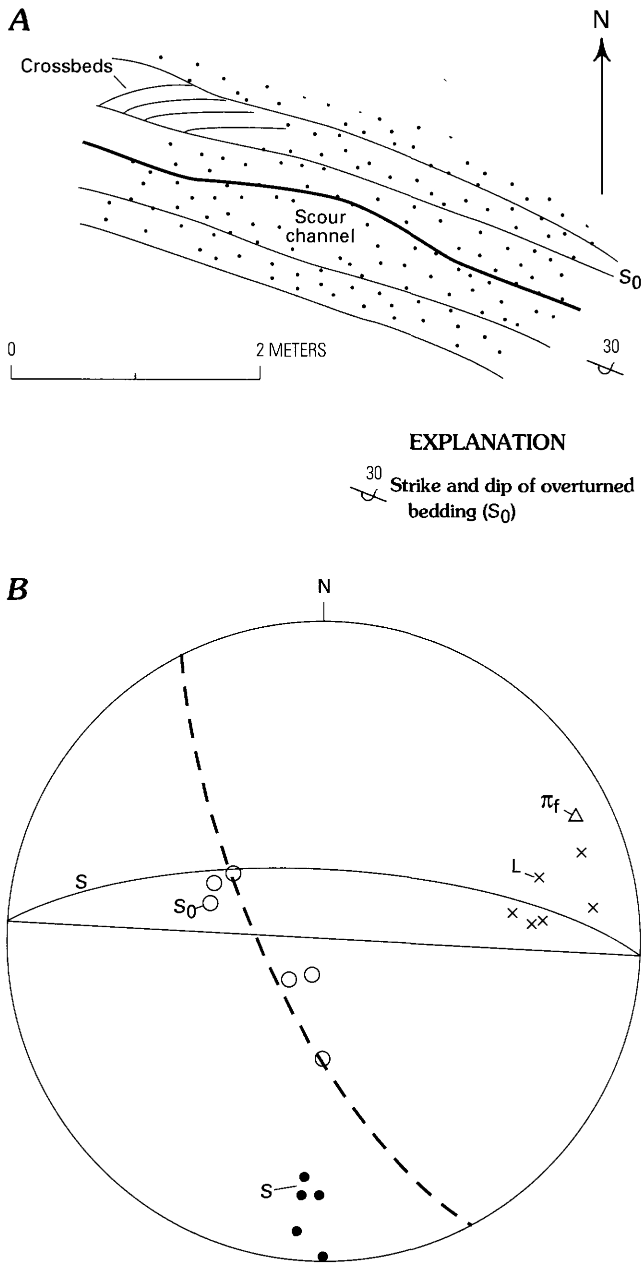


Figure 9. Sturgeon Quartzite at north edge of Felch trough (fig. 3, locality 6). *A*, Diagrammatic sketch of primary sedimentary structures. Bedding expressed by faint color banding in quartzite. Bedding dips northeast. Crossbeds and scour channels in the area (diagrammatically shown) indicate that beds stratigraphically face southwest and are overturned to southwest. Scale is approximate. *B*, Lower hemisphere stereoplot; open circle, pole to bedding (S_0); solid dot, pole to (S_1) foliation; X, bedding-cleavage intersection lineation (L_1). Great circle (dashed line) defines fold axis (triangle) that is nearly coincident with L_1.

In these areas, a subhorizontal foliation (S_1) occurs both in Archean gneiss adjacent to the trough and in the Early Proterozoic strata within the trough.

A second coaxial deformation (D_2) deformed bedding (S_0) and S_1 foliation. Resulting S_2 foliation dips steeply north and strikes generally west-northwest. The D_2 deformation appears to have significantly folded S_1 and D_1 fault planes, such as those at the Groveland mine; accordingly, the pre-D_2 orientation of S_1 and the fault planes is not accurately known.

Toby Lake Trough

Except for a single exposure of Randville Dolomite (Chocolay Group) at the east end of the Toby Lake trough (fig. 3, area 11), only Sturgeon Quartzite is exposed within the trough; the presence of the Michigamme Formation (fig. 13) was inferred by James and others (1961) on stratigraphic grounds. Primary structures in the quartzite, such as cross-bedding and scour channels, unequivocally indicate that bedding, which dips steeply southeast, is overturned toward the north. A spaced fracture cleavage in the quartzite strikes east and dips moderately to the north (fig. 13); it is interpreted as S_1. Archean foliation on either side of the Toby Lake trough is steeply dipping, but it is overprinted in places by a shallower foliation that is interpreted as S_1.

The dip and sense of movement on the Toby Lake fault at this location (fig. 3, area 11) are not known; the fault could dip steeply south, and the Early Proterozoic strata of the trough could represent a fold formed by drag along the fault, as shown in the section of figure 13. Farther east along the Toby Lake fault (fig. 3, locality 11A), Archean gneissic foliation is oriented about N. 75° E. and is nearly vertical. The gneissic fabric is overprinted by zones of fine-grained, foliated mylonite. Small minor folds in the gneiss, whose axes plunge 10°–50° N., 75° E., have a dextral sense of movement in the horizontal plane. Similarly, the orientation of a minor fold in the vertical section suggests that the fault is nearly vertical at this location and the north side is upthrown.

The sense of movement from overturned bedding in the Toby Lake trough suggests northward vergence on the fault with an upthrown southern hanging wall. Thus, the fault appears to be a north-verging, high-angle thrust fault at this location (fig. 3, area 11).

In contrast, to the east along the Toby Lake fault (fig. 3, locality 11A), structural data such as minor folds suggest that the fault is nearly vertical and that the north side is upthrown. Still farther east, the Toby Lake fault is truncated by the North Calumet fault (fig. 3, locality 15), and structural data indicate that this fault is a south-verging, high-angle thrust fault.

Calumet Trough

The Calumet trough is bounded on the north by the North Calumet fault and on the south by the South Calumet

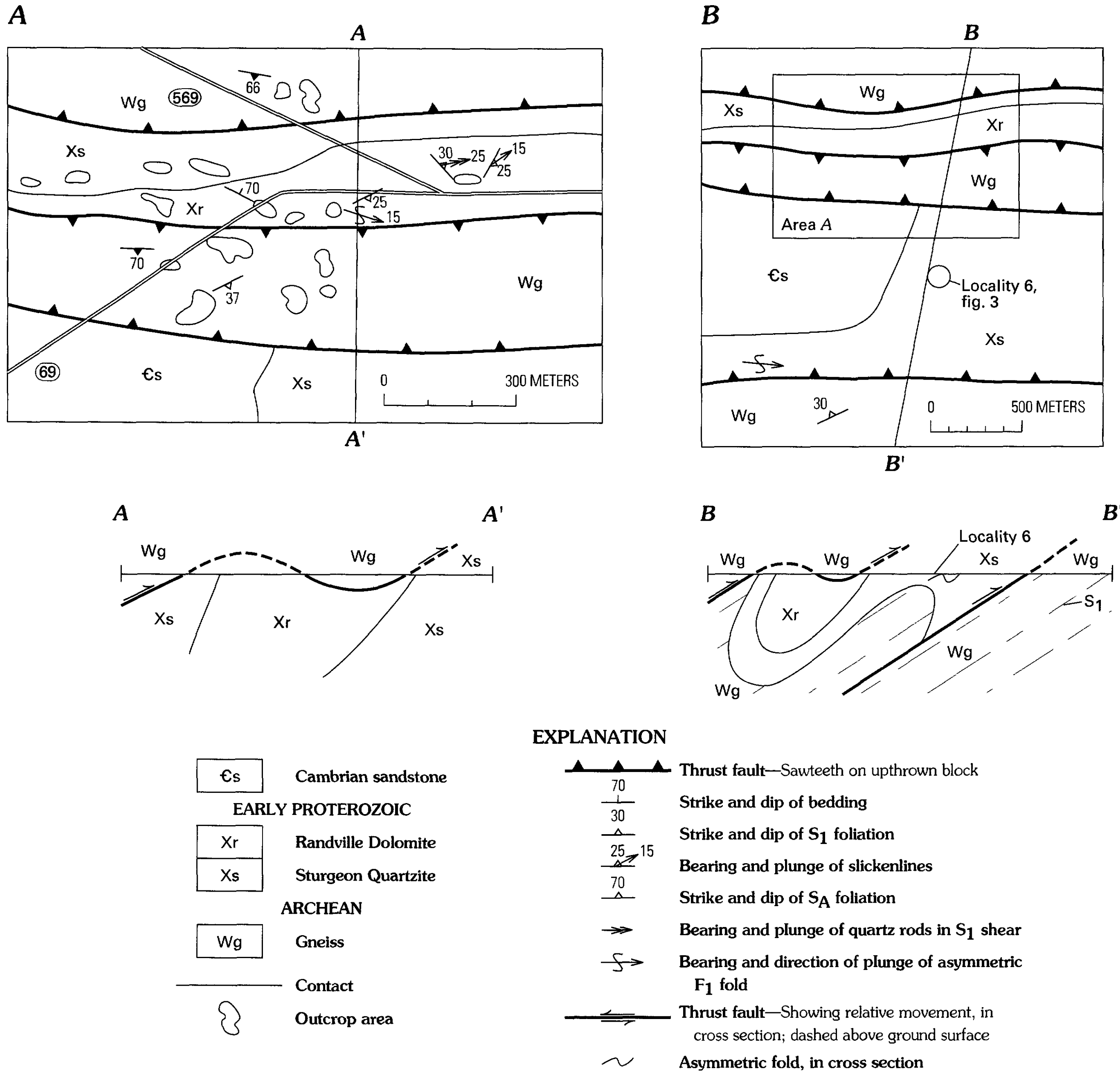


Figure 10. Geology of an area of Felch trough near intersection of old Highway 69 and Highway 569 (fig. 3, locality 7B). *A*, Structure and interpretive cross section *A–A'* of area on north limb of Felch trough. *B*, Structure and interpretive cross section *B–B'* of larger area, inclusive of area of *A*, and also showing locality 6 of figure 3.

fault (fig. 2); the trough appears to extend west-northwest to Horserace Rapids (fig. 3, locality 12).

At Horserace Rapids (fig. 2), on Paint River, graded beds of graywacke of the Michigamme Formation are overturned toward the south (fig. 14*A*). A subhorizontal foliation (S_1) is oriented approximately N. 10° W., 25° SW. This foliation is axial-planar to D_1 folds (F_1) whose axes plunge gently northwest. In turn, S_1 is folded about gently plunging D_2 fold axes, which are shown by L_2 intersection lineations of S_1 and S_2 (fig. 14*A*). The S_2 foliation dips steeply. The southwestward-overturned strata, northwest-oriented fold axes, and subhorizontal foliation together indicate that the Early Proterozoic rocks at Horserace Rapids were deformed by a southwest-verging structural event. A second event (D_2) deformed S_1 and S_0 about northwest-trending fold axes (F_2) having a steeply dipping S_2 foliation.

A structural scenario similar to that at Horserace Rapids exists about 20 km to the southeast, at Steele farm (fig. 3, locality 13). At this locality, southward-facing graywacke beds are oriented N. 80° E., 80° SE. (fig. 14*B*). A subhorizontal S_1 foliation is oriented N. 80° E., 25° SE. S_1 is folded about gently southwest plunging F_2 fold axes. At

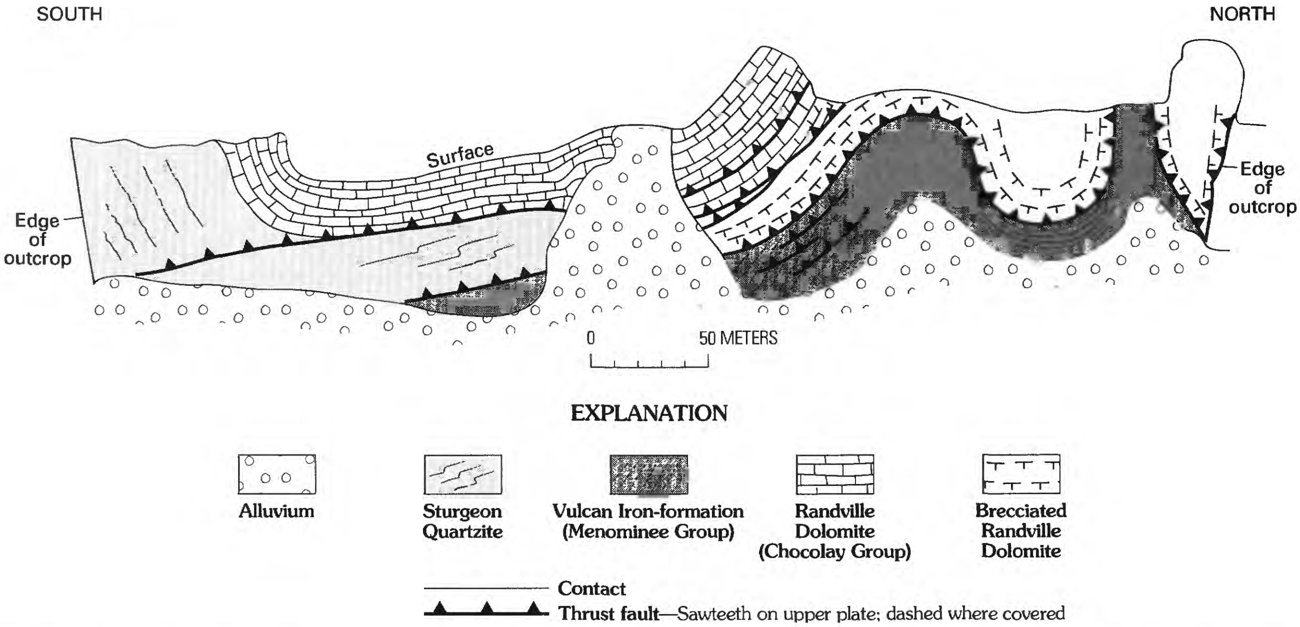


Figure 11. Structural cross section of Groveland mine (fig. 3, locality 9), looking west. Modified from figure 14 of Ueng and Larue (1988). Note low-dipping thrust faults, folding of these thrust planes by a later event, and drag folds diagrammatically shown in the Sturgeon Quartzite. Horizontal scale and vertical scale same.

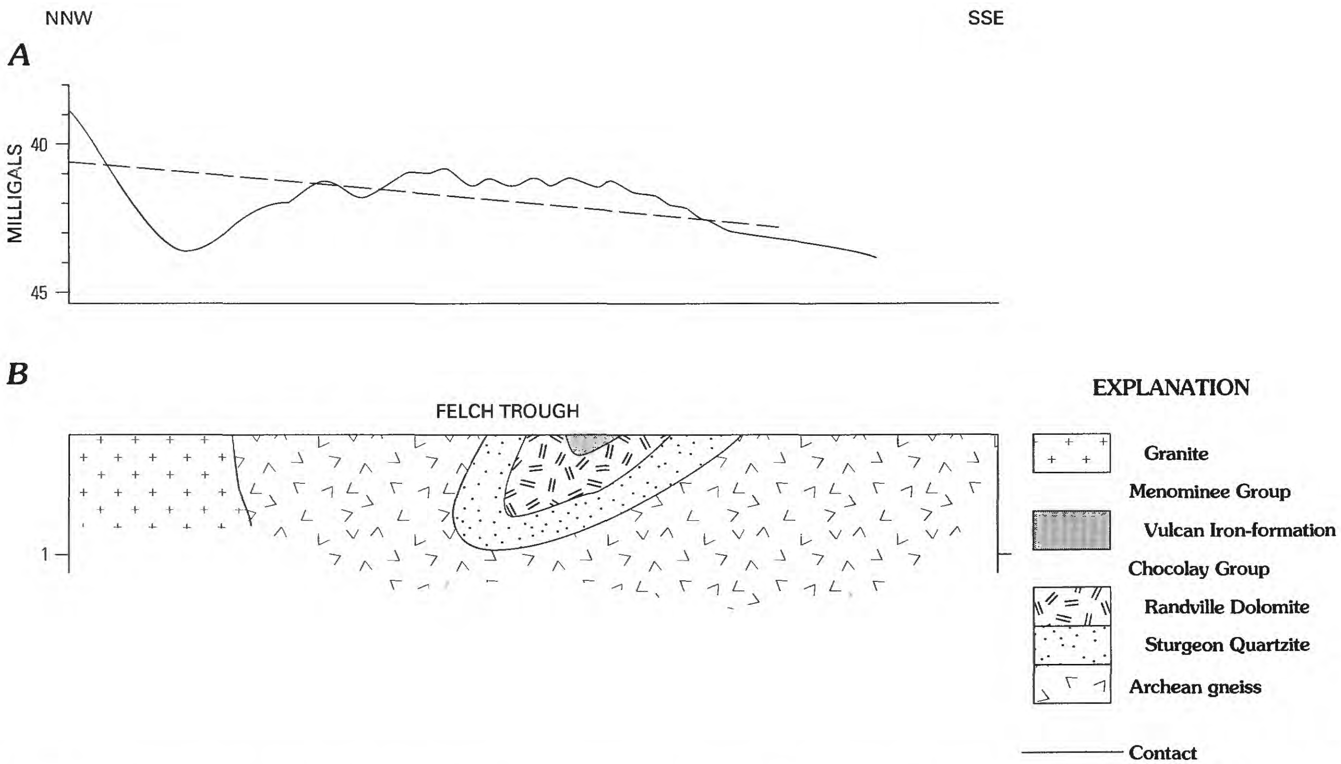


Figure 12. West end of Felch trough. *A*, Bouguer gravity profile (solid line) across Felch trough at traverse labeled 10 (fig. 3). Dashed line, regional gravity gradient, from Klasner and others (1985). *B*, Geologic section of Felch trough incorporating stratigraphic and structural data of the trough near profile of *A*. Note that trough is asymmetrically overturned toward the south and is about 1 km deep. Length of section about 5½ km.

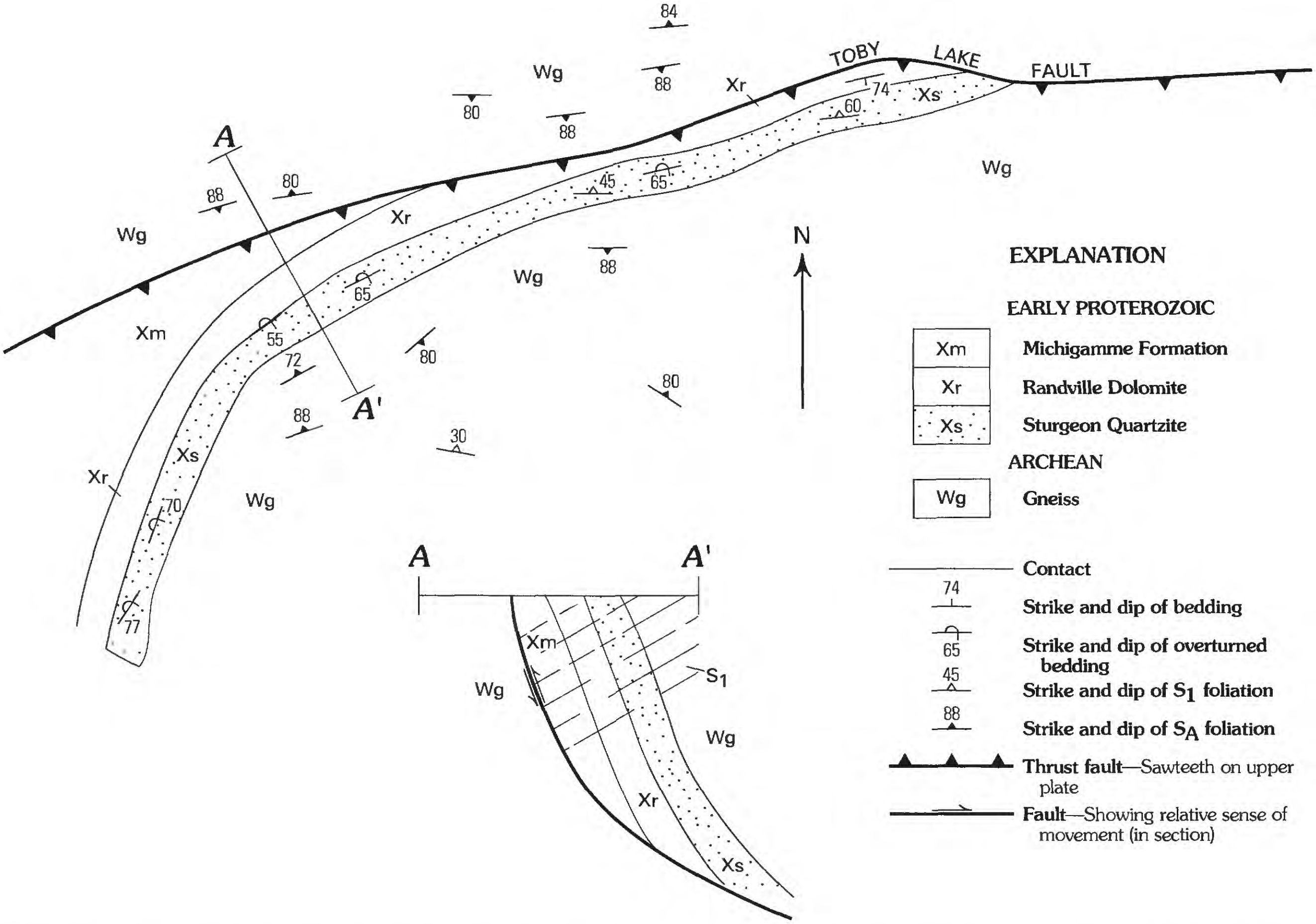


Figure 13. Geology (area 11, fig. 3) of Toby Lake trough region. Note that Sturgeon Quartzite is overturned toward the northwest. Early Proterozoic foliation (S_1) dips moderately northwest. Interpretive cross section *A–A'* suggests that the Early Proterozoic beds were overturned toward the north as part of a north-verging drag fold. The southern, hanging-wall block of the Toby Lake fault is upthrown. East-west length of Xr and Xs outcrop band is about 8½ km.

one place, S_1 has a dihedral fold angle of 40°. F_2 and F_1 fold axes are coaxial. A third deformational event (F_3) is represented by F_3 crenulation folds on S_1 (fig. 14*B*).

Structural data obtained along the North Calumet fault near localities 14 and 15 (fig. 3) provide additional evidence for the sense of vergence. Archean gneissic foliation near the fault dips steeply and strikes northeast (fig. 14*C*). At places, the gneiss is crosscut by zones as much as a meter wide of fine-grained, sugary-textured, foliated mylonite. The mylonite typically dips at a much lower angle than does the Archean foliation. Near the contact with Early Proterozoic strata, the mylonitic fabric in the Archean gneiss strikes northeast and dips steeply northwest (fig. 14*C*). This mylonitic foliation is interpreted to be S_1. Other minor folds in the Archean gneiss near the North Calumet fault have a Z-symmetry, with a dextral sense of movement and nearly vertical fold axes (fig. 14*C*).

Structural data from exposures of Early Proterozoic strata adjacent to the North Calumet fault also indicate southward vergence. Bedding is typically tightly folded, and axial-planar foliation (S_1) is nearly vertical to gently north dipping (fig. 14*D*). Bedding generally dips steeply north and is right way up, but at one locality it is overturned toward the south.

Based primarily on drill-hole and underground mine data, James and others (1961, pl. 4) showed the North Calumet fault as being vertical to steeply north dipping. They noted that the axial planes of folds in this region dip steeply south and that bedding also is steep and slightly overturned toward the north. These observations differ from ours (fig. 14*D*); the only beds that we observed to be overturned are overturned to the south. Bedding (S_0) and S_1 foliation are nearly vertical in this area, and both have been deformed by a second (D_2) event as shown by F_2 fold axes (fig. 14*D*).

We conclude from our accumulated data that the North Calumet fault is a generally high angle, south-verging thrust fault; the thrust possibly dips gently north in its western part. James and others (1961, pl. 4) interpreted drill-hole data to indicate that the North Calumet fault dips north and is upthrown on the north. This is confirmed from our

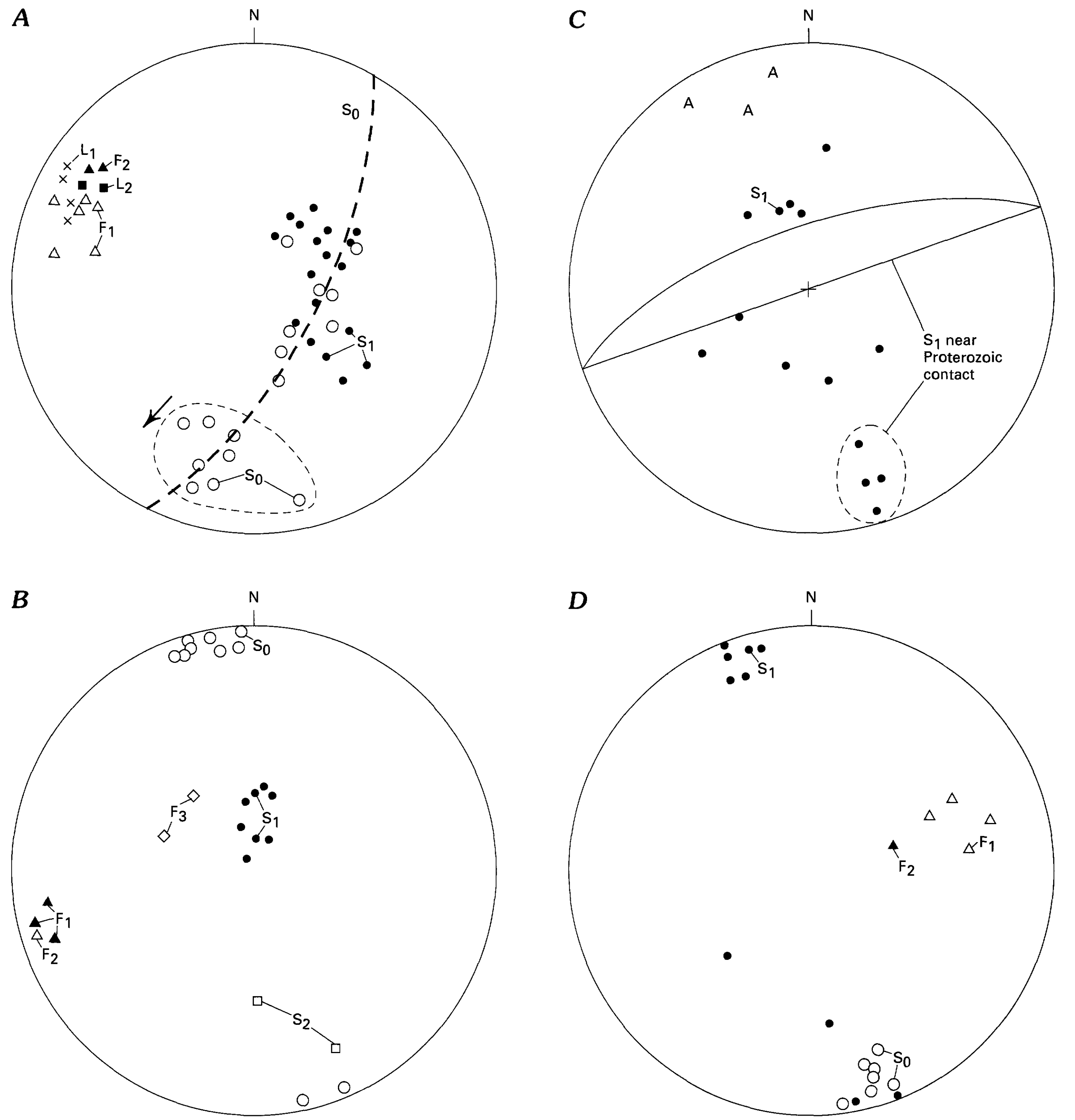


Figure 14. Lower hemisphere stereoplots of structural data from the Calumet trough area. *A*, Structural data at Horserace Rapids (fig. 3, locality 12). Solid dot, pole to S_1 foliation; open circle, pole to bedding (S_0). Several graywacke beds stratigraphically face southward (circled area with arrow). Note that the great circle defines a fold that plunges gently west-northwest. Open triangle, plunge of F_1 fold axis in bedding S_0; solid triangle, F_2 fold axis; X, plunge of lineation (L_1) formed by intersection of bedding (S_0) and foliation (S_1); solid square, plunge of intersection lineation (L_2) of spaced S_2 foliation and S_1 foliation. S_2 is steeply dipping but was not measured. *B*, Structural data from Steele farm area (fig. 3, locality 13). Solid dot, pole to S_1 foliation; open circle, pole to bedding S_0; graywacke beds stratigraphically face south; open square, pole to S_2 foliation; open triangle, plunge of F_2 fold axis in S_1; solid triangle, plunge of F_1 fold axis in S_0; diamond, plunge of F_3 crenulation fold. *C*, Structural data from Archean gneiss along North Calumet fault (area between localities 14 and 15). Solid dot, pole to S_1 mylonitic foliation. Note orientation of S_1 from outcrops near contact with Early Proterozoic strata. A, pole to Archean foliation (S_A). Plus (+), plunge axis of a Z-shaped drag fold in Archean gneiss near the Calumet fault. *D*, Structural data from Early Proterozoic strata adjacent to North Calumet fault (area between localities 14 and 15, fig. 3). Solid dot, pole of S_1 foliation; open circle, pole to bedding S_0; most beds stratigraphically face northward; open triangle, F_1 fold in S_0; solid triangle, F_2 fold axis.

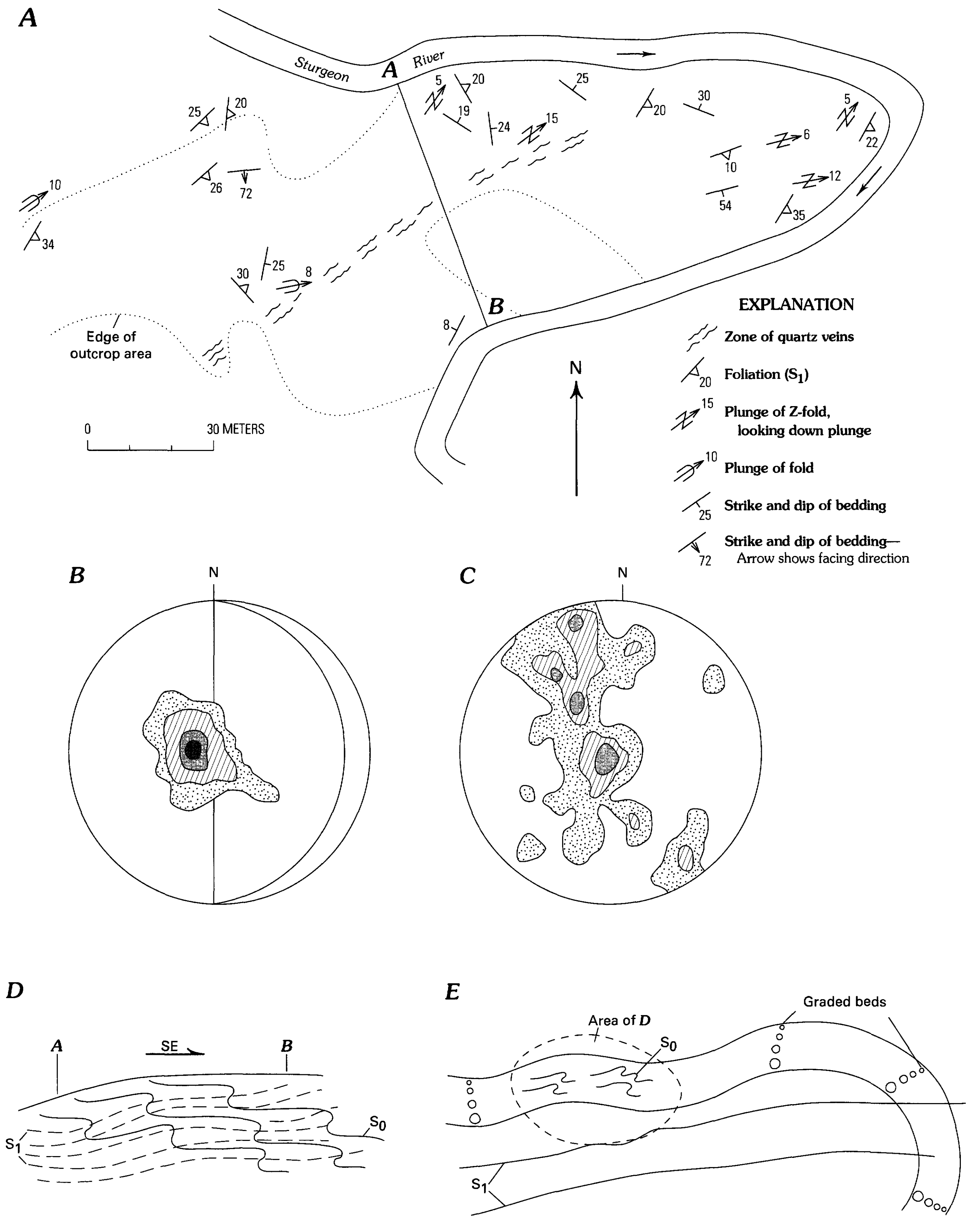


Figure 15. Structure of an outcrop area in Calumet trough, along west branch of Sturgeon River. *A*, Geologic structure at locality 16 (fig. 3). *B*, Contoured lower hemisphere stereoplot of poles to S_1. Contours at 1, 5, 20, 30 percent. *C*, Contoured lower hemisphere stereoplot of poles to bedding (S_0). Contours at 1, 4, 6 percent. *D*, Cross section *A–B* from view *A*. *E*, Interpretive diagram suggesting that this area is on the upper limb of a recumbent fold.

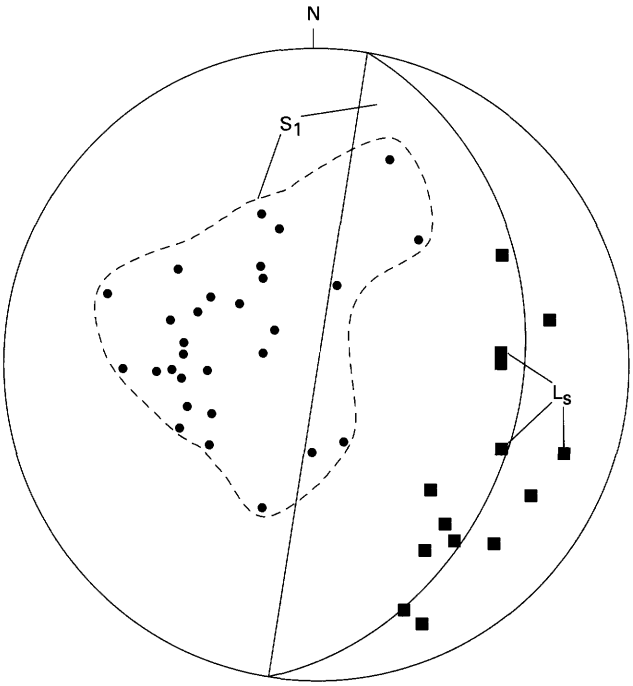


Figure 16. Lower hemisphere stereoplot of Early Proterozoic structures in Archean gneiss terrane of Carney Lake block (fig. 3, area 17). Solid dot, S_1 foliation; solid square, plunge of stretch lineation (L_s) on S_1.

structural measurements of mylonitic foliation along the fault (fig. 14*C*, *D*) and from magnetic data of James and others (1961, plates 2-east half and 4) in the region. For example, positive east-trending magnetic anomalies, which lie just south of the fault above the Early Proterozoic rocks of the Calumet trough, extend obliquely across the fault into the area of Archean gneiss. This suggests that the Archean rocks have been thrust southward, above Early Proterozoic strata of the Calumet trough, overriding the magnetically susceptible rocks of the trough that caused the magnetic anomalies.

Schist and phyllite of the Michigamme Formation are exposed in the Calumet trough along the west branch of the Sturgeon River (fig. 3, locality 16). At this location, S_1 foliation is subhorizontal and forms a gently undulating

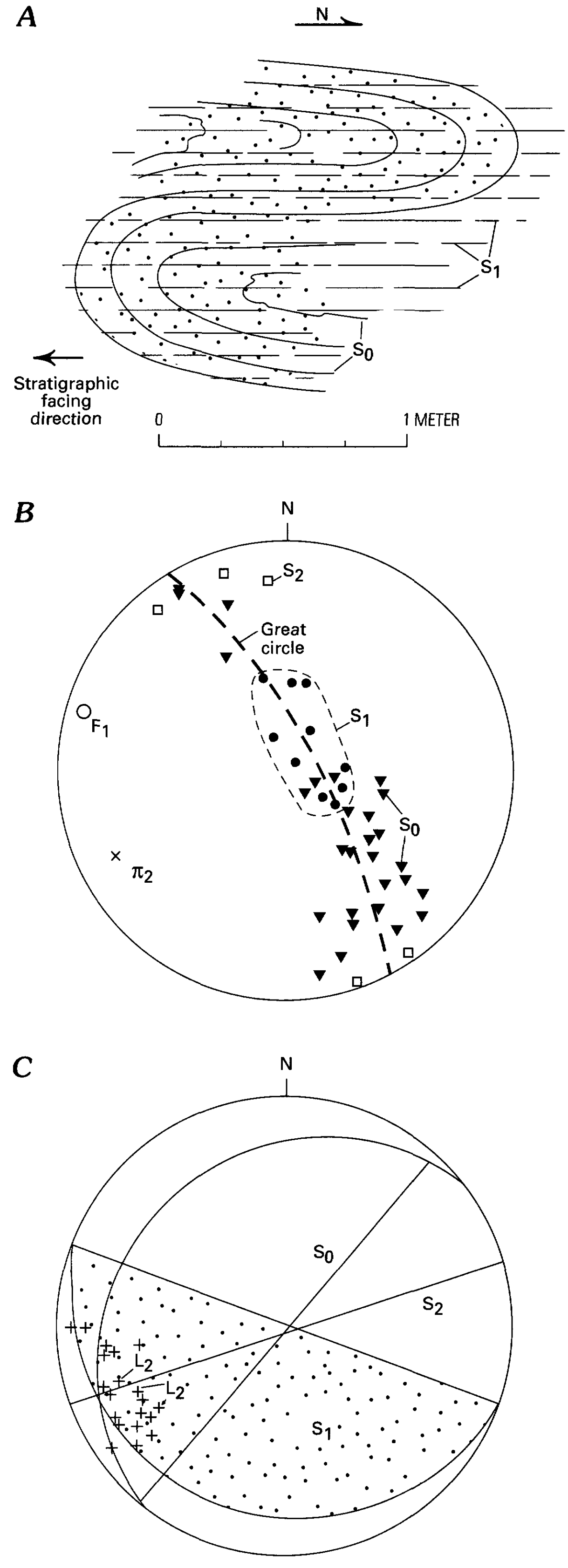


Figure 17 (facing column). Structural data from locality 18 (fig. 3) in Sturgeon Quartzite, west edge of Carney Lake block. *A*, Vertical cross section of north-verging fold in Sturgeon Quartzite. Note horizontal S_1. Bedding stratigraphically faces south in the area, indicating that the quartzite lies on the lower limb of a large-scale recumbent fold. *B*, Lower hemisphere stereoplot. Solid triangle, pole to S_0; open square, pole to S_2 foliation; open circle, measured F_1 fold axis; solid dots enclosed by dashed line, poles to measured S_1 foliation. Great circle interpreted to represent folded S_0 and S_1 foliation with the F_2 fold axis (X) as shown. S_2 foliation is vertical. See L_2 lineations on *C*. *C*, Lower hemisphere stereoplot showing general orientation of bedding S_0, foliation S_1, and foliation S_2. Plus (+), L_2 lineation due to intersection of S_2 and S_1.

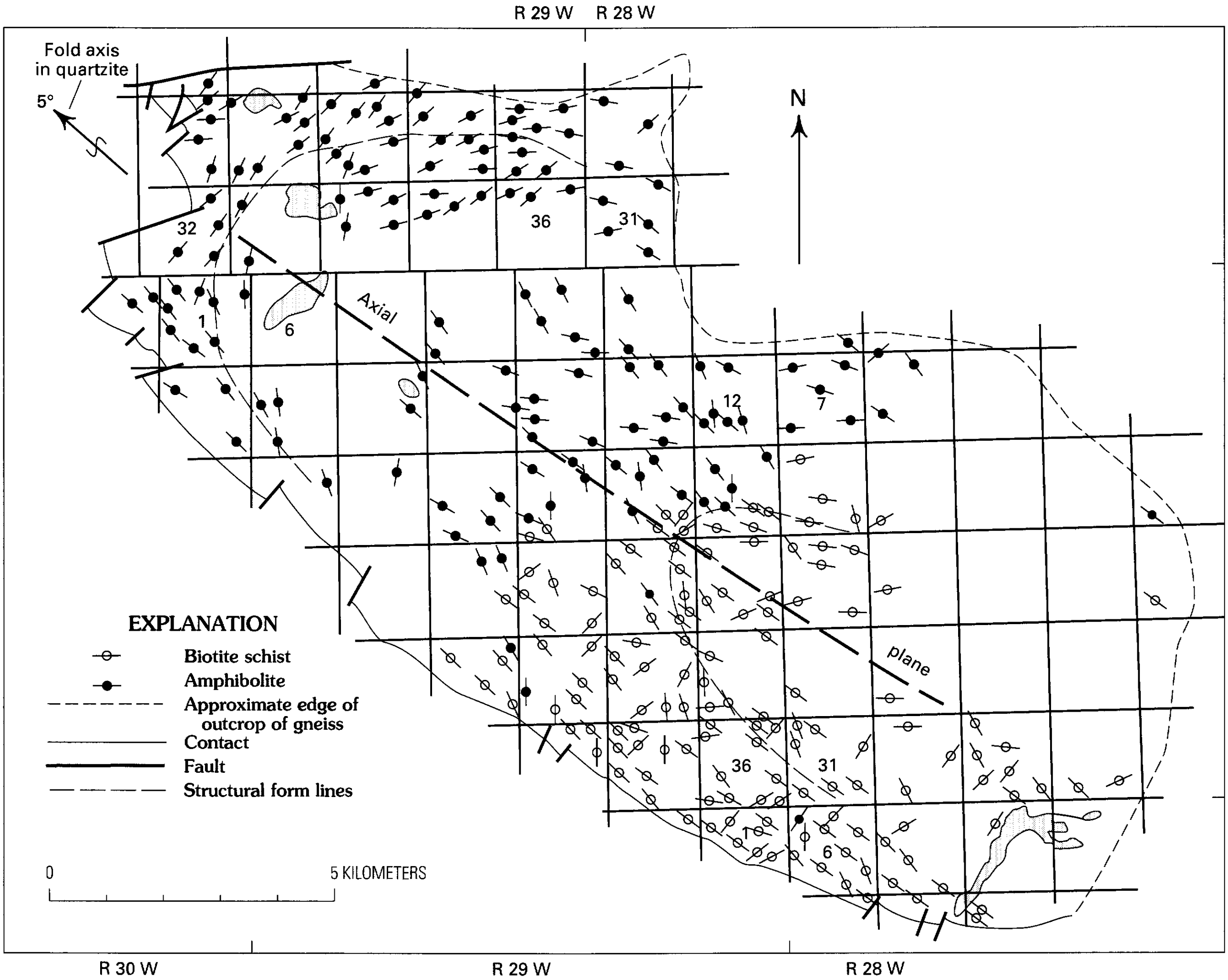


Figure 18. Orientation of long axes of mafic inclusions in Carney Lake Gneiss. Modified from Bayley and others (1966). Note that the orientation of the inclusions defines a fold with a northwest-trending axial plane. Note parallel orientation of fold axis in quartzite.

surface (fig. 15*A*, *B*). Bedding (S_0) generally strikes northeast and has a wide range of dips (fig. 15*C*). The bedding has been deformed into a series of south-verging minor folds with axial-planar S_1 foliation. At one place, a small scour channel shows that the stratigraphic facing in bedding is toward the south. Both S_1 and S_0 have been deformed about northeast-trending, gently plunging fold (F_2) axes with a steep-dipping S_2 foliation. Clearly, the Early Proterozoic strata in this area were deformed by a south-verging event (D_1) that formed a subhorizontal foliation in the rocks. Cross-section sketches (fig. 15*D*, *E*) suggest that this area comprises the upper limb of a south-verging recumbent fold.

Carney Lake Block

Bayley and others (1966) described the Carney Lake Gneiss (fig. 3, area 17) as consisting largely of granite gneiss but also containing minor phases of granodiorite gneiss, syenite dikes, and inclusions. The Archean gneissic foliation (S_A) typically trends northwest and dips steeply. We also observed a subtle, less steeply dipping foliation (S_1) that overprints the Archean foliation (fig. 16). Orientation of S_1 is scattered, and dips range from flat to about 60°. The S_1 surface commonly contains a mineral lineation (L_s), which plunges moderately east to southeast (fig. 16) and which we interpret as a stretch lineation.

The west edge of the Carney Lake Gneiss block is bounded by the Sturgeon Quartzite (Chocolay Group), which is in unconformable contact with the gneiss (fig. 2) and is locally overturned to the southwest. Higgins (1947, p. 489) noted that the Early Proterozoic strata were folded into "a northwest-trending monocline that probably was thrust faulted along its axial plane. During the second phase of deformation this structure was displaced at its northwestern and southeastern ends by vertical tear faults that trend northeast."

Our studies of structures in the Sturgeon Quartzite provide additional information on the nature of deformation in the region and the sense of vergence. The quartzite (fig. 3, locality 18) has been highly deformed. Beds (S_0) are isoclinally folded (fig. 17*A*) and have a low-dipping axial-planar foliation (S_1). Both S_0 and S_1 have been refolded by a second event (D_2) into upright folds having a steeply dipping axial-planar foliation (S_2). The bedding (S_0) is deformed about gently west plunging fold axes (F_1, fig. 17*B*). Foliation S_1 strikes northwest and dips gently southwest (fig. 17*C*), but it, as well as bedding (S_0), is folded about a gently plunging fold axis (π_2) determined from the great circle in figure 17*B*. An axial-planar S_2 foliation strikes northeast and is nearly vertical (fig. 17*B*, *C*). Minor folds, similar to that shown in figure 17*A*, have a northerly sense of vergence, but the folds face south and lie within beds that are overturned toward the south. This pattern indicates that the quartzite lies on the lower limb of a south-verging major fold, possibly a nappe.

Orientations of biotite schist and amphibolite inclusions in the Carney Lake Gneiss define a northwest-trending fold (fig. 18). Because the axial plane of this fold is nearly coincident with the strike of the S_1 foliation and the northwest plunge of the S_1 fold in the quartzite at locality 18 (fig. 3), we suggest that the orientation of the inclusions probably resulted from D_1 deformation. Observations by Higgins (1947, fig. 8) support this interpretation. He concluded that the foliation in the gneiss was deformed ("upturned") along the contact with the quartzite by the same event that deformed the quartzite.

Summary of Kinematic Analyses

Kinematic analyses to determine the direction of Early Proterozoic tectonic transport in each of the domains discussed previously take into account several structural features. One salient feature is a newly recognized low-dipping to subhorizontal S_1 foliation that overprints a subvertical Archean gneissic fabric, and which also occurs in Early Proterozoic strata; S_1 is axial-planar to small-scale asymmetric folds that yield a sense of structural vergence. As noted previously, the symmetry and vergence of isolated minor folds do not in themselves yield a unique sense of overall structural vergence, but when used in conjunction with stratigraphic facing directions, such as overturned bedding and fold symmetry, they can provide reliable kinematic information. The orientation of stretch lineations and fold geometry are among other features that provide pertinent information on the sense of structural vergence.

Structural vergence was determined at several localities in the study area (summarized in fig. 19). Northward-overturned bedding with south-dipping axial-planar S_1 foliation indicates that the Bush Lake trough is north verging (A, fig. 19). This finding is consistent with the observations of Attoh and Vander Meulen (1984) and Attoh and Klasner (1989) that the Bush Lake fault is a reverse fault. The sense of vergence of the Norway Lake fault is not known (B, fig. 19), but a small fault nearby at B_1 is a north-dipping, south-verging thrust fault.

The Carney Lake block is a south-verging feature, and the Sturgeon Quartzite along the southwest edge of the block (fig. 19) is the lower limb of a possible crystalline-core anticline, the axis of which trends northwest. The vergence is indicated by a north-verging, Z-shaped fold in the Sturgeon Quartzite within southward-overturned strata; also, the Sturgeon Quartzite along the southwest edge of the Carney Lake block has been rotated southwestward and is overturned toward the southwest (C, fig. 19). The gneissic foliation within the crystalline core appears to have been folded about a northwest-trending axis during D_1 deformation. The Carney Lake block is bounded to the north by the South Calumet fault, a possible normal fault.

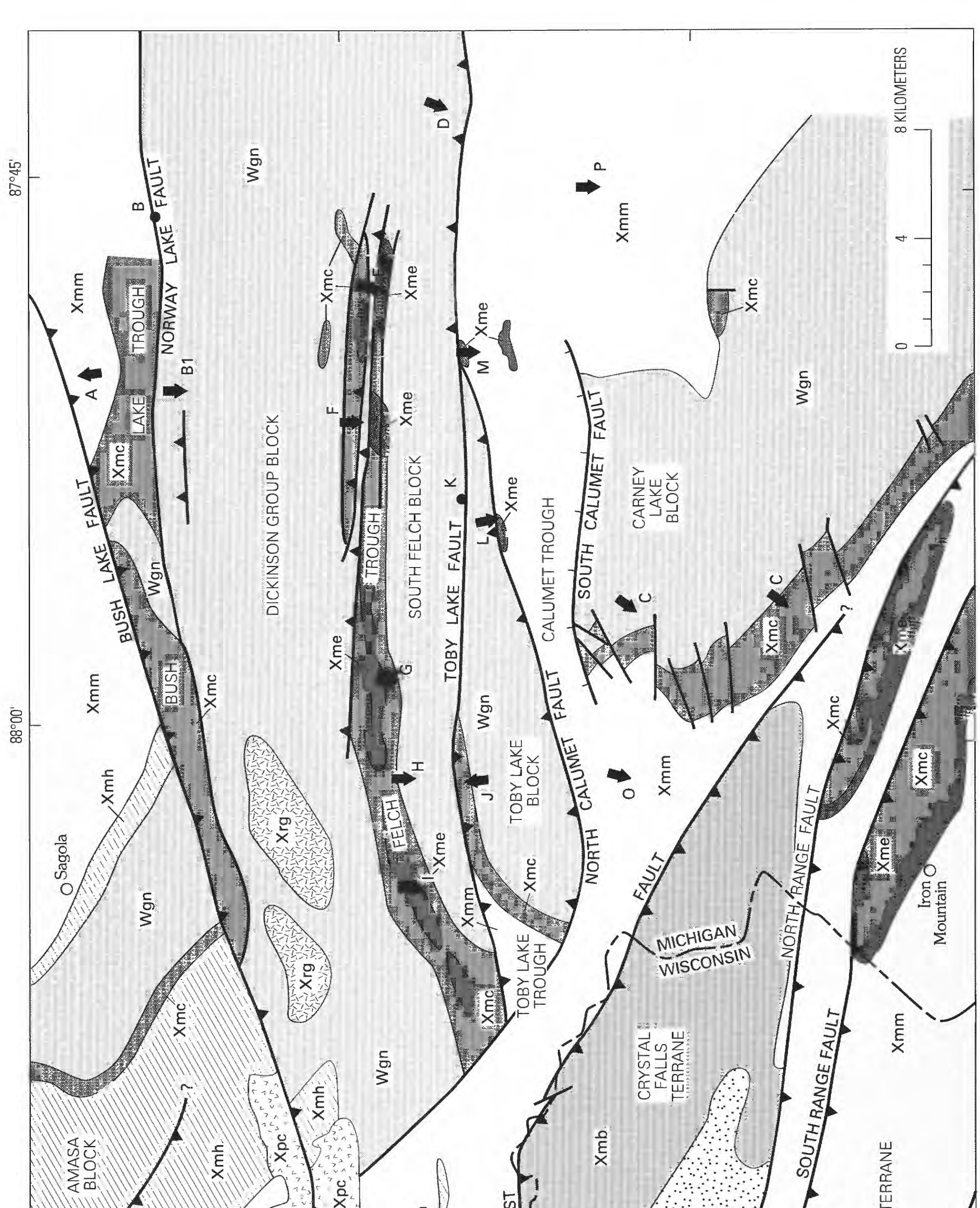
The other Archean crystalline basement blocks (Dickinson Group, South Felch, and Toby Lake) contain an east-trending, nearly vertical Archean gneissic fabric (S_A) that is overprinted by the sporadic, subhorizontal Early Proterozoic S_1 foliation. Data indicating structural vergence in these rocks are sparse; however, in the South Felch block the asymmetric F_1 fold (D, fig. 19) in Archean gneiss containing the low-dipping S_1 foliation indicates southward vergence. This sense of vergence is consistent with the kinematic data from the Felch trough.

Kinematic data along the Felch trough (E through I, fig. 19) indicate that it is a south-verging structure. Diagnostic features include southward-overturned bedding, south-verging asymmetric folds having a low-dipping axial-planar S_1 foliation, stretch lineations, thrust faults (Groveland mine pit), and the overall structure of the trough, which is asymmetric toward the south. We did not confirm Maharidge's (1986) suggestion that the entire stratigraphic succession in the Felch trough may be inverted; we did observe, however, that bedding is overturned in several localities.

Early Proterozoic strata along the Felch trough display a pinch-and-swell pattern (fig. 2). That is, oval basins (swells) within the trough are separated from one another by narrow zones of sedimentary rocks (pinches). This pinch-and-swell pattern probably reflects patterns of original sedimentation. Larue and Sloss (1980) suggested that sedimentation in the largely fault bounded troughs of northern Michigan began in areas of local subsidence, so that uniform sedimentation along the length of the trough would not be expected.

The Sturgeon Quartzite in the Toby Lake trough is overturned toward the north (J, fig. 19), and the sense of drag on the Early Proterozoic strata indicates that the south side of the Toby Lake fault is upthrown. At location K (fig. 19), to the east, however, the Toby Lake fault has a dextral sense of movement and the north side appears upthrown.

Structural data from the North Calumet fault suggest that it is a high-angle, south-verging thrust fault that has a


87°45'
88°00'
88°15'
46°00'
45°45'
0
4
8 KILOMETERS
BUSH LAKE FAULT
NORWAY LAKE FAULT
LAKE TROUGH
BUSH
DICKINSON GROUP BLOCK
AMASA BLOCK
TROUGH
FELCH
SOUTH FELCH BLOCK
TOBY LAKE FAULT
TOBY LAKE BLOCK
TOBY LAKE TROUGH
CALUMET TROUGH
SOUTH CALUMET FAULT
NORTH CALUMET FAULT
CARNEY LAKE BLOCK
BADWATER THRUST FAULT
CRYSTAL FALLS TERRANE
MICHIGAN
WISCONSIN
NORTH RANGE FAULT
SOUTH RANGE FAULT
FLORENCE-NIAGARA TERRANE
NIAGARA FAULT ZONE
WISCONSIN MAGMATIC TERRANES
Sagola
Horserace Rapids
Florence
Iron Mountain
Xmm
Xmc
Xme
Xmh
Xrg
Xpc
Xmb
Xmp
Wgn

dextral component of movement (L and M, fig. 19). This pattern is shown by north-dipping mylonitic shear zones that are axial-planar to south-verging drag folds in the Archean gneiss, dextral drag folds in Archean gneiss, and isolated southward-overturned Early Proterozoic strata of the Calumet trough adjacent to the fault.

All kinematic data from the Early Proterozoic strata in the Calumet trough indicate southward vergence. These data include southward-overturned beds and southward-verging folds in bedding containing low-dipping S_1 axial-planar foliation (N, O, P, fig. 19).

The South Calumet fault, at the south edge of the Calumet trough, possibly is a normal fault upthrown on the south (fig. 20*A*). The fault juxtaposes Archean gneiss of the Carney Lake block with the lower limb of a syncline preserved in the Calumet trough.

The D_1-deformed bedding, Archean gneiss foliation (S_A), and subhorizontal S_1 foliation were deformed by a second (D_2) phase of Early Proterozoic deformation. D_2 deformation folded S_1 foliation into undulating to closely folded surfaces. S_2 foliation is upright and strikes generally eastward. Rocks in the region also were deformed a third time as shown by L_3 crenulation lineations at locality 13 (fig. 3). Also, the dominantly dextral offset on transcurrent faults that cut the Sturgeon Quartzite on the southwest margin of the Carney Lake block (fig. 3) is a late event that postdates D_2.

EXPLANATION

EARLY PROTEROZOIC (1,600-2,500 Ma)

Xrg — Red granite

Xpc — Peavy Pond Complex

Marquette Range Supergroup

Xmp — Paint River Group

Xmm — Michigamme Formation of Baraga Group

Menominee Group

Xme — Sedimentary rocks

Xmh — Hemlock Formation

Xmb — Badwater Greenstone

Xmc — Chocolay Group

ARCHEAN (2,500 Ma and older)

Wgn — Gneiss and metaconglomerate

Contact

Fault—Sense of movement uncertain

Normal fault—Hachures on downthrown side

Thrust fault—Sawteeth on upper plate; queried where extent uncertain

Direction of structural vergence

Figure 19 (above and facing page). Directions of structural vergence in Felch and Calumet troughs area. Except for Bush Lake fault and west part of Toby Lake fault, vergence is southward. Letters mark localities discussed in text.

STRUCTURAL INTERPRETATION

Early Proterozoic deformation in the Felch and Calumet troughs area produced south-verging structures in rocks of the Penokean orogen, which otherwise has an overall northward sense of tectonic transport. Deformation was thick skinned inasmuch as it affected both Archean and Early Proterozoic structures. The presence of a flat-lying S_1 foliation and recumbent asymmetric folds suggests large-scale recumbent folding in the region, and possibly the development of nappes.

A hypothetical vertical section (fig. 20*A*) across the area of the Felch and Calumet troughs illustrates one interpretation of our data. Except for the Bush Lake trough and the Bush Lake fault, nearly all the structural domains in the region were subjected to south-verging deformation. Although deformation probably started as a north-verging event above the Bush Lake fault—a possible sole thrust, as suggested by structures in the Toby Lake trough—it evolved into a south-verging deformational event. Some of the faults, such as the Toby Lake fault, and, perhaps also the Norway Lake fault, may have been inboard (north)-verging faults that were backfolded during subsequent deformation. But the Toby Lake fault is the only one, other than the Bush Lake fault, that has strong evidence for northward structural vergence. The Toby Lake and Norway Lake faults in the model (fig. 20*A*) intersect the ground surface at locations where they are nearly vertical. Similar upward steepening and overturned backthrusts have been described by Tysdal (1986) in the Rocky Mountain foreland of Montana. Structural data along the North Calumet fault suggest that it is a north-dipping, south-verging, high-angle thrust fault with a dextral component of movement in the horizontal plane. Data along the eastern segment of the Toby Lake fault also indicate a dextral component of movement. The south-verging Felch trough is an infolded and faulted remnant of once-extensive Early Proterozoic strata, as are the Toby Lake and Calumet troughs and the remnants of Early Proterozoic strata near the Niagara fault zone (fig. 20*A*). The Carney Lake block is part of a crystalline-core fold, the lower sedimentary limb of which is exposed on the southwest. This interpretation is supported by the presence of north-verging parasitic folds in southward-overturned beds in the Sturgeon Quartzite. Mafic inclusions in the Archean gneiss define a west-northwest fold (fig. 18). The Carney Lake block is bounded on the north by a possible normal fault, the South Calumet fault. The whole package of south-verging crust is bounded to the south by the Niagara fault zone, the suture between the continental margin and the Wisconsin magmatic terranes (Sims and others, 1989) (fig. 1).

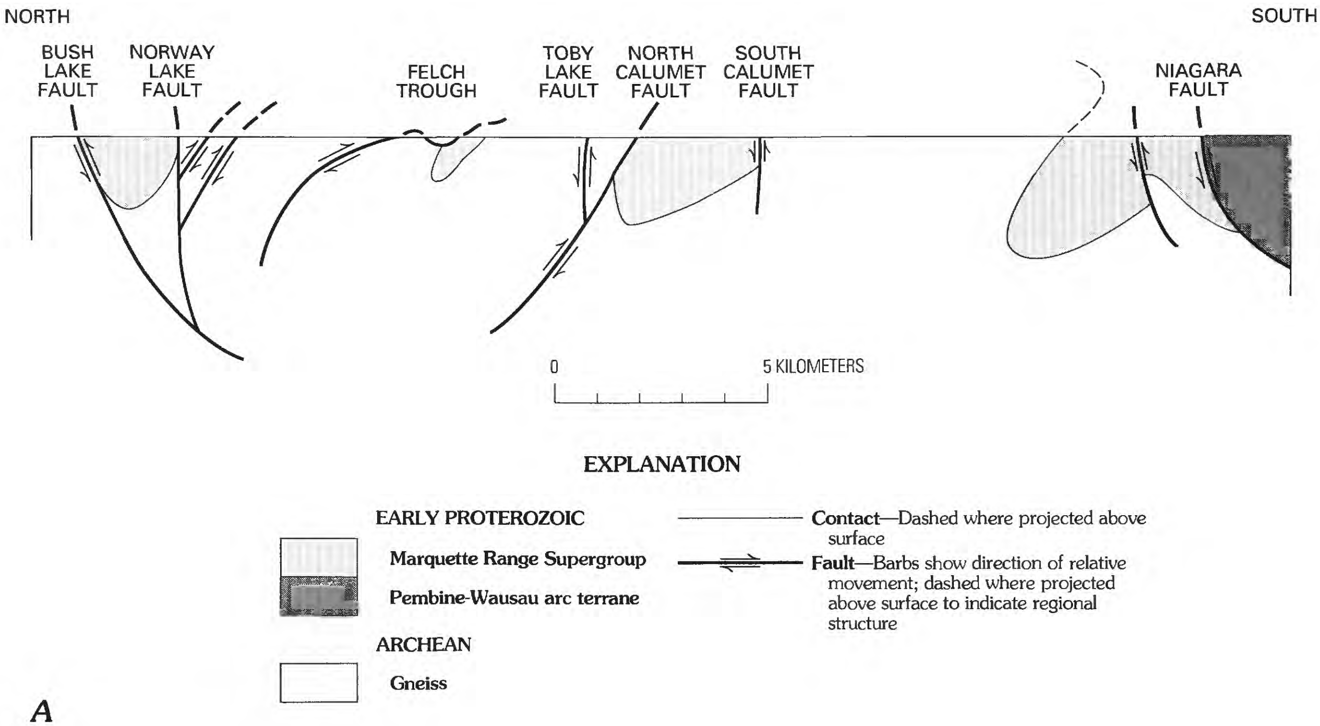


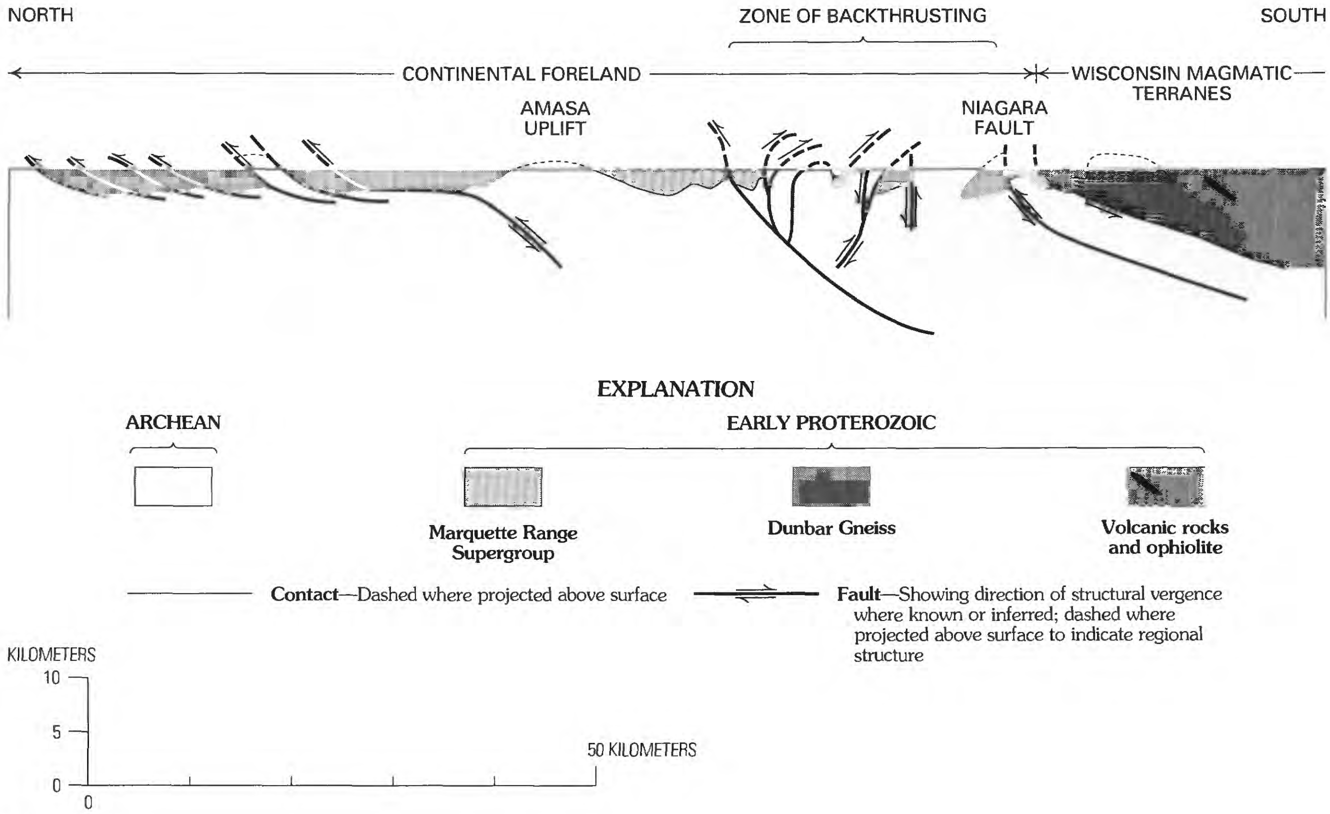
Figure 20 (above and facing page). Cross sections comparing structure in Felch and Calumet troughs area with that in southern Alps. *A*, Hypothetical generalized cross section across area of Felch and Calumet troughs. No vertical scale given. *B*, Interpretive structure in the Felch and Calumet troughs area in relation to cross-sectional structure of the entire Penokean orogen in the continental foreland region of northern Michigan. Cross section extends from L'Anse through Covington to Iron Mountain (fig. 1). Modified from Klasner, Sims, and others (1988). *C*, Structural cross section of the southern Alps, looking north. From Debelmas and others (1983). B and P, sites of backthrusting.

In summary, we propose that the Felch and Calumet troughs area was initially deformed by inboard (north)-verging deformation during accretion of oceanic arc rocks of the Wisconsin magmatic terranes to the south. During the accretionary event, the region evolved into a south-verging deformation zone.

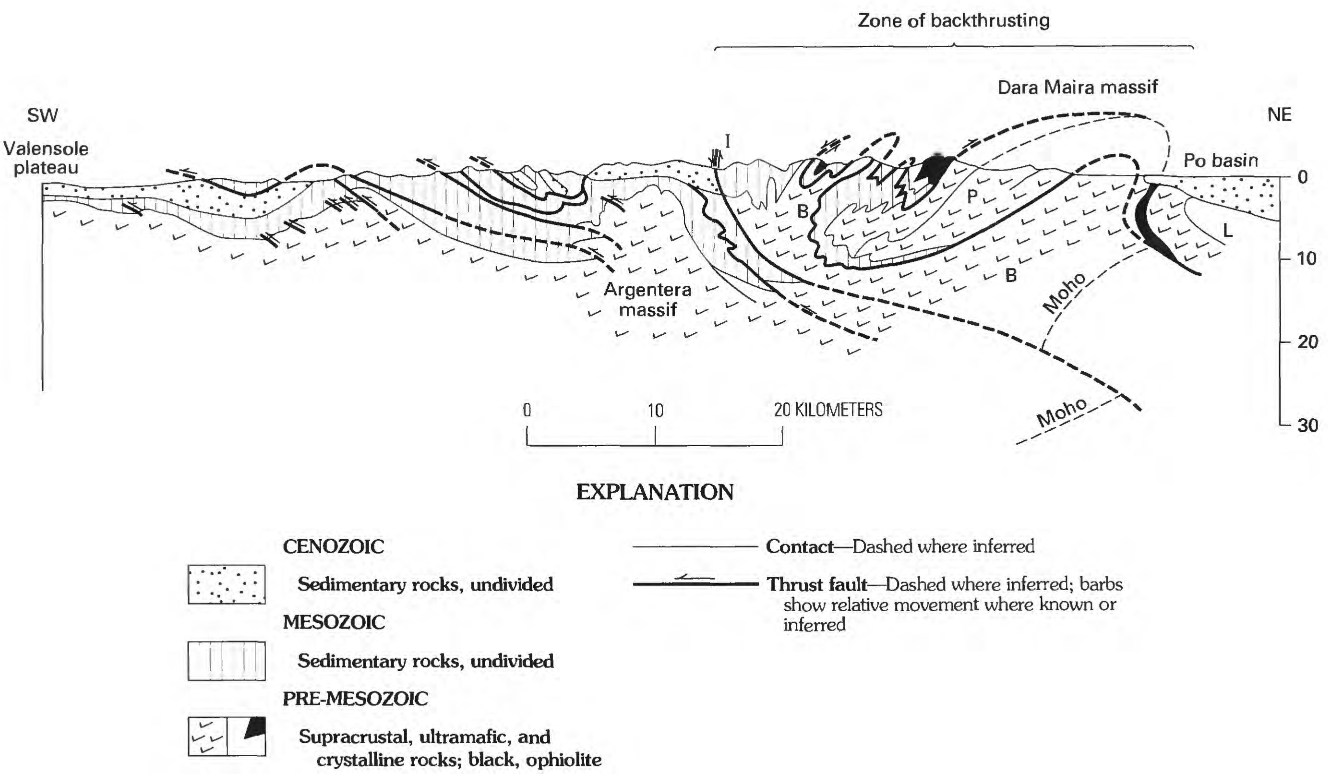
The second (D_2) phase of deformation, characterized by upright folds nearly coaxial with F_1 folds, significantly folded the S_1 surfaces. Such deformation could explain the southeast-plunging lineations found mostly in the southern part of the Carney Lake block. The lineations may have plunged northerly prior to F_2 deformation. A later deformational event (D_3) caused only weak crenulation folding in the region. The offset along wrench faults along the west edge of the Carney Lake block may have resulted from emplacement of the Crystal Falls terrane along the Badwater thrust fault (fig. 2).

STYLE OF PENOKEAN TECTONISM

We conclude that deformation in this part of the Penokean foldbelt was thick skinned and involved significant backthrusting. The south-verging structures in the Felch and Calumet troughs area are opposite to the overall north-verging tectonic transport in the Penokean orogen of northern Michigan (Klasner, Sims, and others, 1988; Klasner and Sims, 1989; Klasner, Ojakangas, and others, 1991). They define a 35-km-wide zone of backthrusting in the overall 100-km-wide zone of deformation in the continental foreland region of northern Michigan. Following the suggestion of Morley (1988), backthrusts as out-of-sequence faults can form in foreland thrust belts where an abrupt change occurs in thickness of the thrust sheet. Morley called upon models of Davis and others (1983) and Chapple (1978) to show that backthrusts occur where the critical taper of the thrust wedge is such that forward propagation of the thrust sheet cannot be maintained. Hence, the thrust wedge is thickened by backthrusting and internal deformation until a critical taper is accomplished and the in-sequence forward thrusting and folding can continue. Morley (1988) also noted that backthrusts are generally accompanied by vertical uplift and the development of high-angle reverse faults, and the Norway Lake and Toby Lake faults certainly are high-angle


NORTH
ZONE OF BACKTHRUSTING
SOUTH
CONTINENTAL FORELAND
WISCONSIN MAGMATIC TERRANES
AMASA UPLIFT
NIAGARA FAULT
EXPLANATION
ARCHEAN
EARLY PROTEROZOIC
Marquette Range Supergroup
Dunbar Gneiss
Volcanic rocks and ophiolite
Contact—Dashed where projected above surface
Fault—Showing direction of structural vergence where known or inferred; dashed where projected above surface to indicate regional structure
KILOMETERS
10
5
0
0
50 KILOMETERS

B


Zone of backthrusting
Dara Maira massif
SW
NE
Valensole plateau
Po basin
I
B
P
L
B
Argentera massif
Moho
Moho
0
10
20
30
0
10
20 KILOMETERS
EXPLANATION
CENOZOIC
Sedimentary rocks, undivided
MESOZOIC
Sedimentary rocks, undivided
PRE-MESOZOIC
Supracrustal, ultramafic, and crystalline rocks; black, ophiolite
Contact—Dashed where inferred
Thrust fault—Dashed where inferred; barbs show relative movement where known or inferred

C

reverse faults in which the sense of movement was largely vertical.

The zone of backthrusting in the Felch and Calumet troughs area occurs at the edge of the continental foreland, a short distance north of the Niagara suture, which separates oceanic crust from continental crust. Here, an abrupt change occurs in the thickness of the thrust sheet, and we suggest that the thrust sheet was thickened by backthrusting until the northward-verging thrust system could propagate northward onto the foreland. Such backthrust systems are not uncommon. Morley (1988) cited several examples of backthrusting from the Canadian Rockies (Price, 1986), the Alps (Tricart, 1984), and elsewhere; in these examples, large-scale backthrusting accompanied in-sequence thrusting.

That nappes may exist in the Felch and Calumet troughs area is suggested by the pervasive, low-dipping foliation (S_1) in Archean and Proterozoic rocks. Except for the Sturgeon Quartzite on the southwest edge of the Carney Lake block and in the Toby Lake trough, evidence is lacking for an overturned or inverted stratigraphy on a large scale. However, this does not preclude the possibility that nappes now eroded from the Penokean orogen may have existed at higher tectonic levels.

The deeply eroded 1,850 Ma Penokean orogen is similar structurally to the much younger Alpine orogen, as illustrated in figure 20*B*, *C*. Debelmas and others (1983), as well as Tricart (1984), noted that tectonism in the southern Alps comprised at least two major phases of deformation. The first phase consisted of westward (inboard) thrusting with isoclinal folding and nappe emplacement. The second phase was characterized by "backwards thrusting (retrocharriage)," as shown by eastward-verging, overturned folds (Debelmas and others, 1983, p. 84). These zones of backthrusting are labeled "B" and "P" in figure 20*C*. Debelmas and others (1983, p. 84) also noted that "evolution * * * begins with a westward phase of thrusting * * * followed by a classical eastward thrusting." All these motions are linked with high-pressure metamorphism. The presence of ophiolites and ultramafic rocks (L, fig. 20*C*) indicates that this structural domain is accreted terrane.

An uplifted zone of basement rocks in the southern Alps, the Argentera massif, lies just west of a major fault (I, fig. 20*C*), and the fault extends westward over the massif. Farther west, basement rocks were not involved in the deformational picture, and according to Debelmas and others (1983, p. 85), "flysch was stripped off and * * * together with sub-Brianconnais substratum, was folded and thrust westward * * *."

The crustal profile of the Penokean foldbelt in northern Wisconsin and Michigan (fig. 20*B*), although involving rocks some 1,820 m.y. older than those of the southern Alps, exhibits many similarities to the Alpine profile. The zone of backthrusting in the Felch and Calumet troughs area together with high-pressure metamorphism in the area of the Peavy Pond Complex (fig. 2) (Attoh and Vander Meulen, 1984), and the existence of accreted oceanic crust, including ophiolite, are associated features also observed by Debelmas and others (1983) in the Alps. The Bush Lake fault in the Penokean orogen is a master thrust that extends inboard over a basement uplift, the Amasa uplift, and appears in much the same attitude as fault I in figure 20*C*, which extends inboard over the Argentera massif, a basement uplift. Inboard of the Amasa uplift, turbidite deposits—flysch derived from the Wisconsin magmatic terranes (Barovich and others, 1989)—were transported onto the continental margin along sole thrusts, which apparently did not involve the basement to any appreciable extent. This thin-skinned deformation is similar to that depicted in the western part of the area of figure 20*C* from the southern Alps.

Despite the similarities we recognize between the crustal profiles of the southern Alpine and the Penokean orogens, the substantial age difference in the rocks (1,850 Ma versus 30 Ma) causes some difficulty in making direct comparisons. Erosion of the Penokean orogen has removed most of the supracrustal strata and their enclosed evidence of tectonism, and has exposed a deeper tectonic level. Thus it is not possible to assess the complexity of deformation in these higher level rocks, as can be done in the Alps. The Alps, retaining such rocks, may provide an insight into the possible style of deformation in the supracrustal rocks of the Penokean orogen. Possibly these higher level Early Proterozoic supracrustal strata were deformed by an initial north-verging phase of deformation into stacked nappes, which were subsequently deformed by backthrusting in a manner similar to that outlined by Debelmas and others (1983) for the southern Alps.

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