The Mountain Shear Zone, Northeastern Wisconsin—A Discrete Ductile Deformation Zone Within the Early Proterozoic Penokean Orogen

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Chapter A

The Mountain Shear Zone, Northeastern Wisconsin—A Discrete Ductile Deformation Zone Within the Early Proterozoic Penokean Orogen

By P. K. SIMS, J. S. KLASNER, and Z. E. PETERMAN

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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The Mountain Shear Zone, Northeastern Wisconsin—A Discrete Ductile Deformation Zone Within the Early Proterozoic Penokean Orogen

By P.K. Sims, J.S. Klasner,[1] *and* Z.E. Peterman

Abstract

The Mountain shear, a discrete ductile deformation zone containing mylonitic rocks, largely obliterates older fabrics (S_0/S_1) in metavolcanic and granitoid rocks of Early Proterozoic (≈1,860 Ma) age. A relatively undeformed quartz diorite body (1,812.7±3.6 Ma; U-Pb zircon) that was intruded late in the deformational history of the shear zone provides a firm minimum age on the time of shearing.

The shear zone trends N. 55°–60° E., is from 1 to 2.5 km wide, and has a prevailing steep mylonitic foliation (S_2) and stretching lineation (L_2). The southeastern margin transects north-trending country rocks and is gradational across a width of 100 m or more. The shear zone is truncated on the southwest, northwest, and northeast by undeformed anorogenic intrusive rocks of the 1,470 Ma Wolf River batholith, which had no perceptible structural effect on the country rocks or the shear zone.

S-C mylonite fabrics and stretching lineations indicate that the southeast block of the Mountain shear zone is upthrown relative to the northwest block. Field relationships and kinematic data suggest that the sense of movement in the horizontal plane was dextral, as indicated by the apparent clockwise rotation of S_0/S_1 toward parallelism with the southeast margin of the shear zone and the small right lateral offset of a granodiorite body deformed in the shear zone.

Strain analyses indicate that the shear zone represents heterogeneous simple shear with accompanying heterogeneous volume change because (1) domains of relatively low strain are preserved within the shear zone, (2) the nature, magnitude, and orientation of displacement vary both across and along the zone, (3) the L-S tectonites were formed primarily by plane strain but locally were subjected to apparent constriction, and (4) the rocks were differentially subjected to both volume loss and volume gain along the length of the shear zone. The magnitude of both flattening and stretching increased from the southeast margin toward the center of the zone.

The shear zone was formed 35–45 million years after the collisional event (≈ 1,850 Ma) that sutured the Wisconsin magmatic (arc) terranes to the Early Proterozoic continental margin along the Niagara fault zone. Shearing could have resulted from an unrecognized continent-continent or continent-arc collision to the south or southeast of the study area.

INTRODUCTION

The existence of an extensive belt of well-exposed mylonitic rocks near Mountain, in Oconto County, northeastern Wisconsin (fig. 1), was revealed during reconnaissance geologic mapping in 1980. A detailed geologic map (scale 1:24,000) was prepared during 1985 and 1986 (Sims, 1989), and detailed structural studies were carried out later to determine the nature of the deformation and the sense of displacement. The purpose of this report is to (1) describe the structural features within the shear zone, (2) outline and document the sequence of deformational events, (3) discuss the kinematics, including an analysis of strain, and (4) relate structures within the shear zone to the evolution of the Penokean orogen as a whole.

The Mountain shear fits the definition of Ramsay (1980) of a discrete zone of ductile deformation. The term mylonite, as used herein, follows the terminology of Wise and others (1984, p. 393): "Mylonite is a general term for coherent rocks with at least microscopic foliation, with or without porphyroclasts, characterized by intense syntectonic crystal-plastic grain-size reduction

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

of the country rock to an average diameter less than 50 microns (0.5 mm) and invariably showing at least minor syntectonic recovery/recrystallization."

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M.G. Mudrey, Jr. of the Wisconsin Geological and Natural History Survey assisted Sims in reconnaissance mapping of the Mountain area in 1980, and Bruce Brasaemle, G.L. LaBerge, and K.J. Schulz assisted in the geologic mapping during 1985–1986. In this report, Sims is responsible for the general geologic relationship at both local and regional scales, Klasner is responsible for the detailed field structural analysis and the strain analysis, and Peterman is responsible for the geochronology. The manuscript benefitted from critical reviews by R.L. Bauer and E.H. DeWitt.

GEOLOGIC SETTING

The Mountain shear zone is within the Early Proterozoic Penokean orogen (fig. 1), which lies along the southeastern margin of the Archean Superior province of the Canadian Shield. The Penokean orogen consists of two assemblages, a northern continental-margin assemblage of metasedimentary rocks in northern Michigan (Marquette Range Supergroup and its equivalents), which overlies Archean basement, and a southern assemblage of island arc volcanic-granitic rocks, termed the Wisconsin magmatic terranes (Sims, 1987). The two are juxtaposed along the Niagara fault zone, believed to be a paleosuture (Sims and others, in press). The northern (Pembine-Wausau) terrane of the Wisconsin magmatic terranes was accreted to the continental margin about 1,850–1,860 Ma (Peterman and others, 1985; Sims and others, 1985); during the collision, rocks within both terranes were regionally deformed and metamorphosed.

The Mountain shear zone is one of several discrete shear zones in the Pembine-Wausau terrane (LaBerge and Myers, 1983; Klasner and LaBerge, 1985) that formed after the culmination of regional deformation and metamorphism.

MOUNTAIN AREA

Geology

Major rock units within and adjacent to the Mountain shear zone are Early Proterozoic metamorphosed volcanic and volcanogenic sedimentary rocks, assigned to the Waupee Volcanics, and an unnamed granodiorite body (unit Xg) and its deformed and metamorphosed equivalent in the shear zone (unit Xgn, fig. 2). The metavolcanic rocks and the granitic gneiss in the shear zone are overlain by a local meta-conglomerate, the Baldwin Conglomerate. The metavolcanic rocks are intruded by the Hines Quartz Diorite, a relatively undeformed body confined to the shear zone. Early Proterozoic rocks within and southeast of the shear zone are truncated on all sides by anorogenic granitic rocks of the Middle Proterozoic (1,470 Ma; Van Schmus and others, 1975) Wolf River batholith.

The volcanic rocks and granodiorite were subjected to regional deformation and upper greenschist facies metamorphism prior to the shearing. These rocks were converted in the shear zone to mylonitic schists and gneisses predominantly of lower amphibolite facies (Sims and others, 1986). The Baldwin Conglomerate was deformed during the shear deformation, but less intensely than the volcanic and granitoid rocks. The Hines Quartz Diorite, which has a U-Pb zircon intercept age of 1,812.7±3.6 Ma (fig. 3), was emplaced after or near the end of the ductile deformation, and this places a firm minimum age on the time of shearing.

Regional Structure

Metavolcanic rocks southeast of the shear zone have a penetrative schistosity (S_1) expressed mainly by aligned biotite and hornblende that are subparallel to depositional layering (S_0). The schistosity is axial planar to tight F_1 folds, and is expressed by pancake-shaped clasts that would fall within the region of apparent flattening on a Flinn (1962) diagram. S_1 in the granodiorite (unit Xg, fig. 2) is expressed mainly by flattened inclusions of metavolcanic rocks, principally amphibolite. The intensity of S_1 foliation southeast of the shear zone is variable, indicating that the deformation was not homogeneous. For example, S_1 foliation in felsic volcanic rocks (unit Xwf, fig. 2) is more intense than in the granodiorite (unit Xg) and in mafic lava flows (unit Xwm). A summary plot of measured foliation orientations outside the shear zone is given in figure 4; the calculated mean (S_1) foliation is N. 8° E., 90°.

As noted in table 1, S_1 fabric was observed at isolated outcrops within the Mountain shear zone; accordingly, the F_2 deformation of the shear zone was superposed on rocks that had been deformed previously to varying degrees during the regional F_1 event.

Mountain Shear Zone

The Mountain shear zone, which sharply truncates and is distinctly younger than the regional foliation

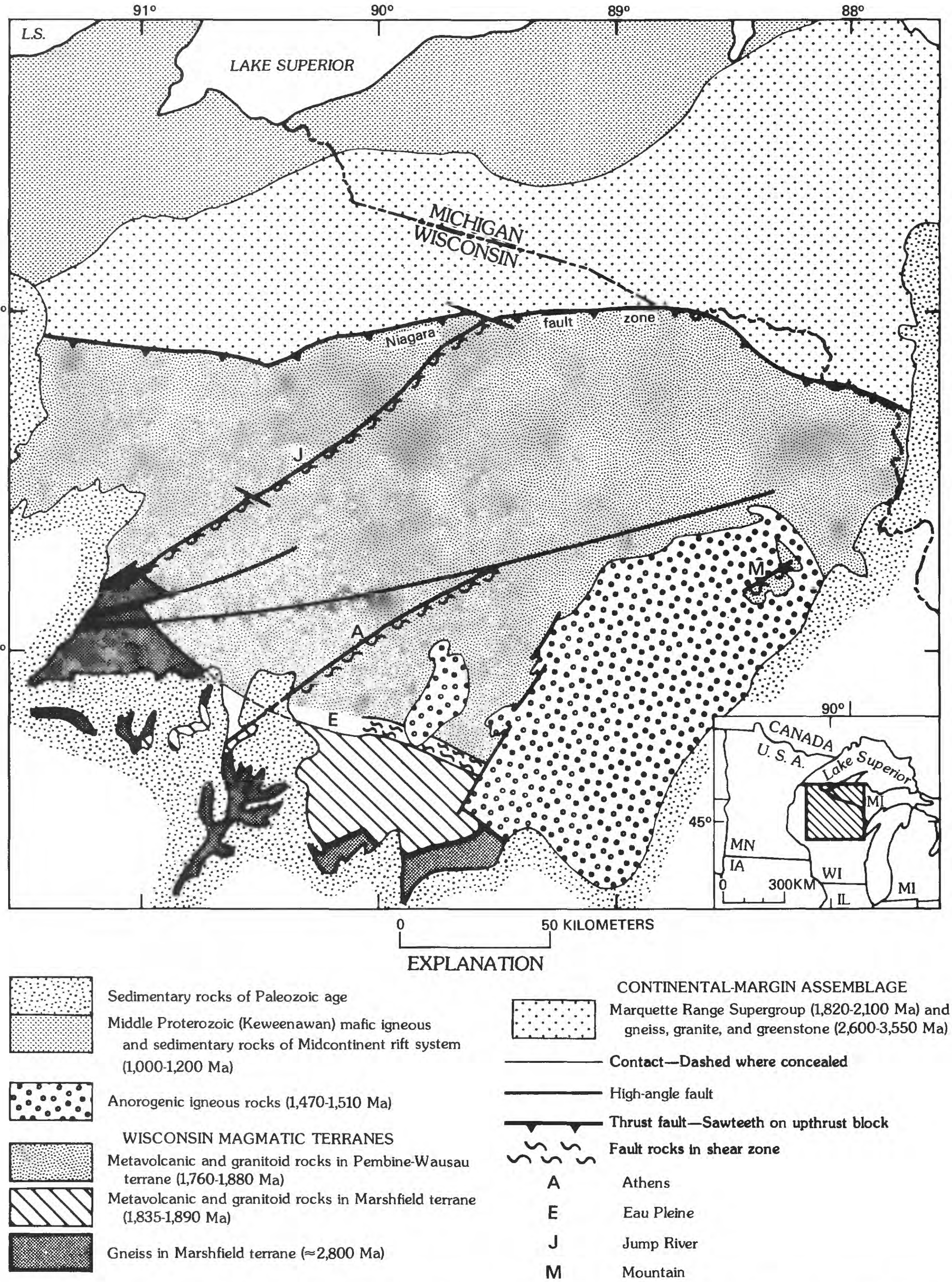

Figure 1. Generalized geologic map of eastern part of the Lake Superior region, northern Wisconsin and Michigan, showing major features of Early Proterozoic Penokean orogen. Modified from Sims (1987).

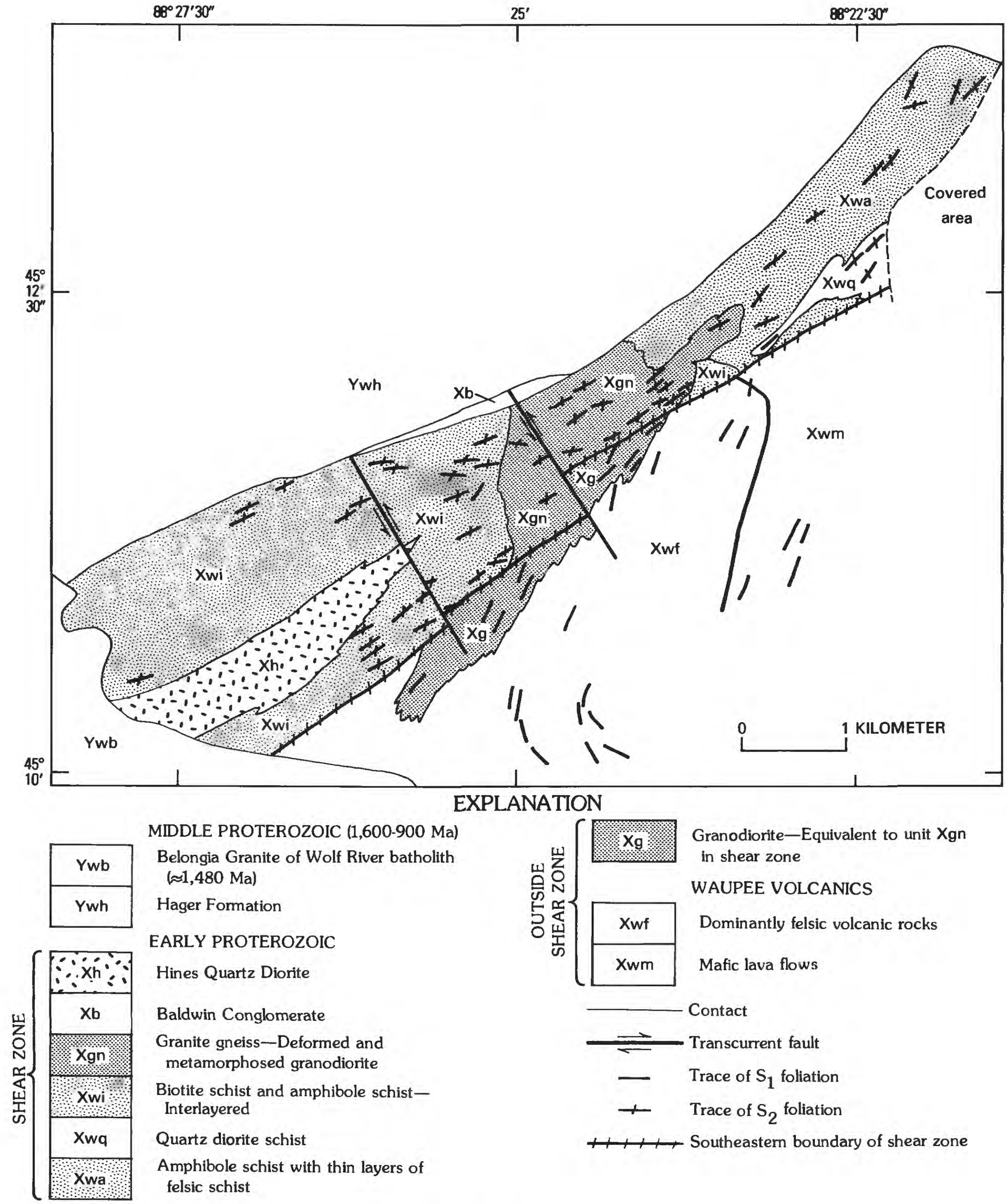

Figure 2. Geologic map of Mountain shear zone and vicinity, northeastern Wisconsin.

(S_0/S_1), strikes N. 55°–60° E. It has a steep dip, and an exposed width of 1–2.5 km. Two northwest-trending, sinistral (left lateral) faults transect the shear zone near its midpoint (fig. 2), and the major one offsets the southeastern edge of the zone about 500 m. These structures are probably also shear zones, as judged from the presence of several small-scale, northwest-trending ductile zones in the Mountain shear zone. The southeastern margin of the Mountain shear zone—the transition from mylonitic to nonmylonitic rocks—is relatively abrupt, although narrow zones of high strain subparallel to the main zone occur sporadically for a distance of 100 m or more outward from the margin. Elsewhere, the shear zone is truncated by younger granitic rocks of the 1,470 Ma Wolf River batholith, which had little or no apparent tectonic or metamorphic

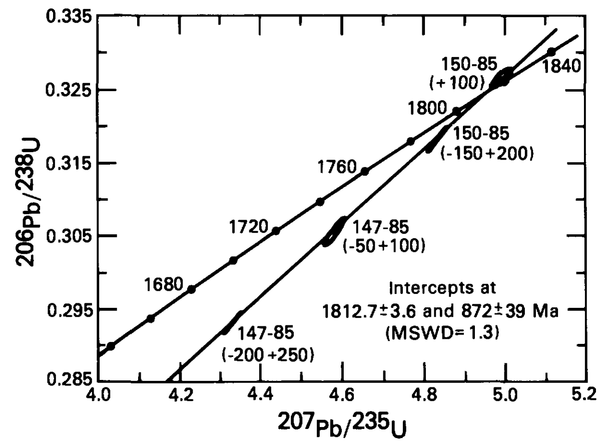

Figure 3. Concordia plot of zircon data for sample 147–85 and 150–85 of Hines Quartz Diorite. Intercepts defined by four fractions of zircon are 1,812.7±3.6 and 872±39 Ma. Numbers in parentheses are mesh sizes.

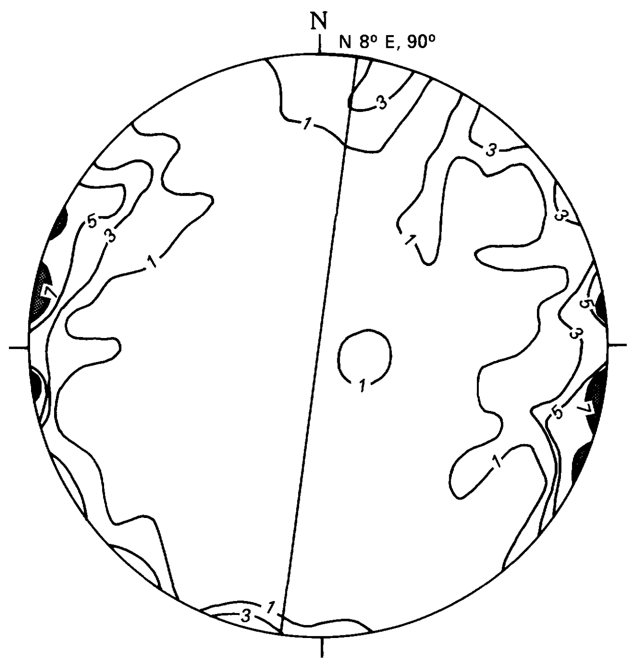

Figure 4. Contoured, equal-area projection of 68 poles to foliation outside of shear zone. Contours are 1, 3, 5, and 7 percent. The great circle (N. 8° E., 90°) is the calculated mean.

effect on the rocks in the shear zone. Accordingly, neither the full width nor the length of the shear zone is known.

The shear zone is characterized by a prominent foliation (S_2), an accompanying stretching lineation (L_2), minor younger S-structures, and by partial tectonic transposition of S_0/S_1 and formation of folds. In the shear zone, biotite and quartz are predominantly recrystallized, whereas plagioclase and microcline, which are less ductile than the matrix, are only partly recrystallized. The deformed rocks are mainly protomylonite or orthomylonite (Wise and others, 1984). Biotite is present in irregular, anastomosing trains, commonly associated with recrystallized plagioclase and, locally, microcline. The biotite and associated feldspar are very fine grained, commonly ≈0.2 mm in diameter. Much of the plagioclase, however, remains as porphyroclasts as much as 5 mm in diameter, which commonly have mantles (type IP structures of Hanmer, 1982) of fine-grained (≈0.1–0.2 mm) plagioclase. Quartz tends to be recrystallized into lenses or rods which are comparable in size to the plagioclase porphyroclasts. These lenses actually are coarse-grained aggregates of individual sutured grains less than 0.5 mm in diameter. Commonly, the quartz lenses and rods contain inclusions of plagioclase and biotite and, locally, sphene and amphibole.

Principal Structural Features

The geometry and complexity of deformation of rocks within the Mountain shear zone are shown schematically in an isometric diagram of part of the zone (fig. 5) and by stereoplots of structural data from selected, critical outcrops within it (fig. 6).

Within the shear zone, the rocks are penetratively deformed by structures assigned to F_2 and younger events (table 1), but domains of relatively nonmylonitized rocks as much as tens of meters across remain. The F_2 structures consist mainly of an S-surface (S_2; C, fig. 5) resulting from tectonic layering and a mylonitic foliation; a stretching lineation (L_2) expressed by elongate clasts (E, fig. 5), rodding, and biotite streaks; and folds of the S_0/S_1 surface (D, fig. 5). The resulting composite structures are L-S tectonites. Younger ductile fold structures (F_3, F_4 (F and G on fig. 5)) and kink bands related to brittle deformation (H on fig. 5) are superposed locally on the older, dominant structures, but do not appreciably modify the distribution of the rocks.

Narrow zones of high strain are present outside the main shear zone, as at locality IIb (fig. 6), where north-striking S_1 foliation is overprinted by a local zone of crenulation folds that strike N. 70° E. and dip steeply southeast, parallel to a 1-m-wide shear zone that is subparallel to the trend of the main shear zone.

Deformation was inhomogeneous within the shear zone. In the granitic rocks (unit Xgn), which lacked appreciable initial anisotropy, S_2 consists dominantly of mesoscopic and microscopic, thin anastomosing, biotite-rich zones and oriented, flattened aggregates of quartz. S-C mylonites (as defined by Berthé and others, 1979) in the biotite-rich zones resemble type I of Lister and Snoke (1984). Throughout the shear zone, the C foliation is most prominent (see fig. 9). A related lineation is expressed by biotite aggregates and, especially, quartz rods. In strongly anisotropic rocks such as bedded tuff, S_2 is expressed at places by brecciated and boudinaged,

Table 1. Sequence of events, structural elements, and nature of events in the Mountain shear zone

Event	Structural element	Symbol	Explanation	Nature of event
Deposition	Bedding, pillow structures, intrusive contacts.	S_0	Primarily is layering between felsic and mafic rocks.	Original depositional and intrusive features.
F_1	Regional foliation; flattened clasts.	S_1	Best observed south of shear zone, but present in isolated outcrops within shear zone.	Flattened clasts suggest regional compression.
F_2	Foliation	S_2	Tectonic layering, mylonitic foliation in granitic gneiss (unit Xgn).	Foliation associated with simple shear due to relative upthrow from southeast. L_{2a} formed by fold of S_1 and S_0. L_{2b} caused by simple shear associated with upthrow.
	Fold axes	L_{2a}	Folds of S_2 plane.	
	Long axes of strained clasts. Stretched lineations.	L_{2b}	Stretched clasts that lie in S_2 plane.	
F_3	Foliation	S_3	Geometric element. Not generally observed.	Late folding that created a west-northwest-trending fabric.
	Fold axes	L_3	Seen as fold axes on S_2 surface.	
F_4	Foliation		Fabric is poorly developed. Appears to fold F_3 fabric.	Rarely observed. Yielded a north-northwest-trending fabric.
	Fold axes	L_{4a}		
	Lineations	L_{4b}		
	Shears			Shears are parallel to cross faults.
F_k	Kink bands	S_k L_k	Variously oriented kink bands and fold axes associated with kink bands.	Late-stage brittle deformation. Not systematically studied. Number of events not known.

brittle (siliceous) layers, representing S_0/S_1 foliation that has been tectonically transposed into parallelism with S_2. However, at many other places segments of S_0/S_1 surfaces have not been completely transposed, and folds are present that contain axial planar S_2 foliation (see D, fig. 5). In interlayered mafic and felsic volcanic rocks, especially in the area northeast of the cross faults (locality V, fig. 6), the felsic layers commonly have a conspicuous S_2 foliation expressed by recrystallized biotite that obliterates S_0/S_1, whereas some of the mafic layers, especially those at a large angle to S_2, have a relict S_0/S_1 and only a weak S_2 foliation expressed by aligned hornblende or chlorite.

Stereoplots from localities studied in detail within the shear zone (black areas in fig. 6) show variable, generally northeast trending S_2 foliation having a steep dip to the northwest or southeast. At locality III, a layered schist (unit Xwi) has a well-developed N. 58° E. foliation that dips steeply southeast; the long axes of deformed clasts (E, fig. 5) plunge steeply east (L_{2b} on stereonet III, fig. 6). At locality IV, S_2 foliation strikes N. 36° E. and dips steeply southeast; elongate quartz aggregates (L_{2b}) plunge steeply east. At locality V, S_1 foliation is preserved in the fold crest within a mafic layer of a folded layered felsic-mafic volcanic rock, and axial planar S_2 foliation is most intensely developed in the felsic layer. At locality VI—an orthomylonitic granitic gneiss (unit Xgn)—S_2 foliation strikes N. 53° E. and dips steeply southeast. At locality VII, on the northern margin of the shear zone, undeformed Hager Feldspar Porphyry of the Hager Formation cuts deformed Baldwin Conglomerate. Clasts within the conglomerate are variably deformed: quartzite and granitoid clasts are least strained, whereas mafic volcanic clasts are highly strained. Flattened volcanic clasts have an S_2 foliation that strikes N. 56° E. and dips steeply northwest. At locality VIII, S_2 foliation in mafic schist strikes N. 48° E. and dips steeply northwest. Three sets of kink bands that plunge southwest (L on stereonet VIII) are superposed on the S_2 foliation. At locality IX, intermediate to mafic tuff has a penetrative S_2 foliation that strikes N. 68° E. and is vertical; the long axes of volcanic clasts also plunge vertically. At locality X, interlayered felsic and mafic volcanic rocks have a conspicuous S_2 foliation, N. 72° E., 68° SE., which dips somewhat less steeply than elsewhere in the shear zone.

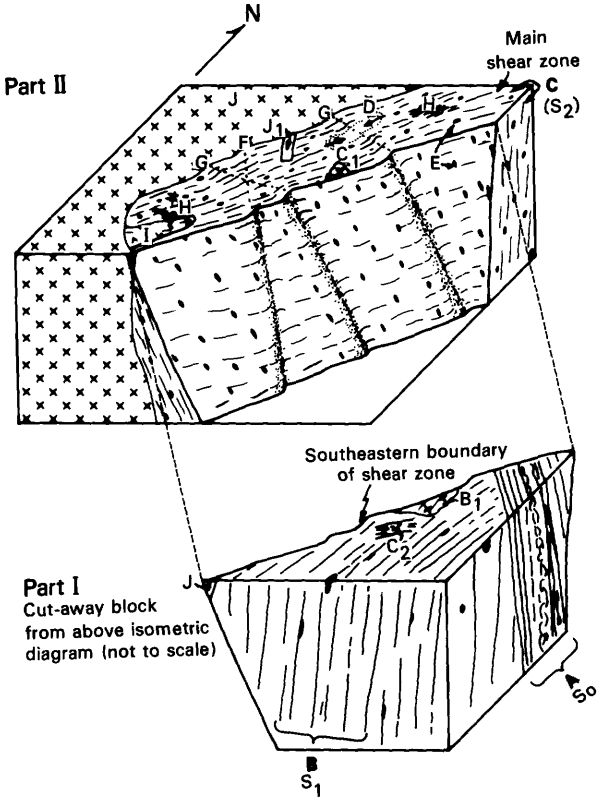

Figure 5. Isometric sketch (diagrammatic, not to scale) illustrating the general geometry and deformational elements of the shear zone and adjacent country rock. See table 1 for discussion of symbols and sequence of events. Deformational elements are as follows: A, Primary bedding (S_0); B, F_1 generation foliation (S_1); C, F_2 generation foliation (S_2); B_1, granodiorite (unit Xg) body deformed by F_1 event; C_1, same granodiorite body as B_1 but deformed into gneiss (unit Xgn) by both F_1 and F_2; C_2, small F_2 deformational domain outside of main shear zone; D, domain of weak F_2 deformation where pre-F_2 fabric elements (S_0,..dotted lines, and S_1) are preserved; E, strained clasts that define steeply plunging stretch direction (L_{2b}); F, F_3 fold axes (L_3) and axial planes (S_3); G, F_4 fold axes (L_4) and axial planes (S_4); H, late-stage kink folds or bands; I, late syntectonic (F_2) to mostly posttectonic Hines Quartz Diorite intrusion within main shear zone; J, anorogenic granite pluton of 1,470 Ma Wolf River batholith and accompanying undeformed felsic dikes (J_1) in main shear zone.

Younger Structures

Three minor, more restricted deformational events followed the main (F_2) deformation in the shear zone (table 1). An (F_3) episode of deformation is represented by local folds whose axial traces trend northwestward (F, fig. 5). The nature of these folds can be seen in figure 7, which shows multiple folded gneissic layering in the granitic gneiss (unit Xgn, fig. 2). Here, the S_1 surface is folded by F_2, and both the S_1 surface and the axial traces of the F_2 fold axis have been folded by F_3 deformation. Axial traces of the F_3 fold trend northwest.

Additional data on the F_3 event and evidence for an F_4 deformation are given in figure 8. Stereoplot *A* (fig. 8*A*) from locality XII (locality shown in fig. 6), clearly shows F_3 deformation: S_2 foliation is folded about east- or east-southeast-plunging fold axes (L_{3a}). Plot *B*, from locality X, shows that S_2 foliation strikes N. 72° E. and dips moderately southeast, but the spread in distribution of S_2 poles indicates that S_2 has been folded by later events, as suggested by girdles 3 and 4 and corresponding beta axes, B_3 and B_4. Stereoplot *C* (fig. 8*C*), also from locality X, provides additional data on F_4. To facilitate interpretation, we have plotted girdle 4 and beta axis B_4 from fig. 8*B*; we have also plotted the orientation of the S_2 foliation plane from a selected outcrop within the area of locality X (fig. 6). Evidence for F_4 folding was observed in these outcrops. Open folds having wavelengths of about 1 m and amplitudes of about 30 cm have fold axes that plunge steeply southeast (L_{4a}, stereoplot *C*, fig. 8*C*). Intersection of measured S_4 foliation in the outcrop and S_2 foliation forms a prominent rodding that also plunges southeast (L_{4b}, stereoplot *C*). The F_4 deformation (G, fig. 5) is expressed locally by ductile shear zones interpreted as being related to the northwest-striking, sinistral faults that transect the Mountain shear zone (see fig. 2). A 4-cm-wide ductile shear zone of this set transects strongly foliated granitic gneiss (fig. 9) at locality XIII (fig. 6), just southwest of the major sinistral fault. Boundaries of the shear zone and the foliation within the zone are parallel to the S_4 axial planar fabric of fig. 8*C* and to the transcurrent faults.

The last episode of deformation is kink banding (H, fig. 5), which represents late-stage brittle deformation in the shear zone. These structures were not systematically studied.

Kinematic Analysis

The sense of movement during the F_2 shear deformation has been determined from S-C fabrics (Berthé and others, 1979; Lister and Snoke, 1984) in mylonitic granitic gneiss, by orientation of stretch fabrics (long axes of strain ellipsoids), and from other field data such as described by Simpson and Schmid (1983) and Simpson (1986). S-C mylonite fabrics (fig. 10) in granitic gneiss from several localities show that the southeast block of the Mountain shear zone is upthrown relative to the northwest block. Stretch fabrics, as indicated by the orientation of the long (X) axes of strain ellipses, also suggest the same sense of movement. Stereoplots at localities III, IV, and IX (fig. 6) show that stretch axes (L_{2b}) plunge steeply south to east. This steeply plunging stretch fabric is possibly caused by a simple shear couple

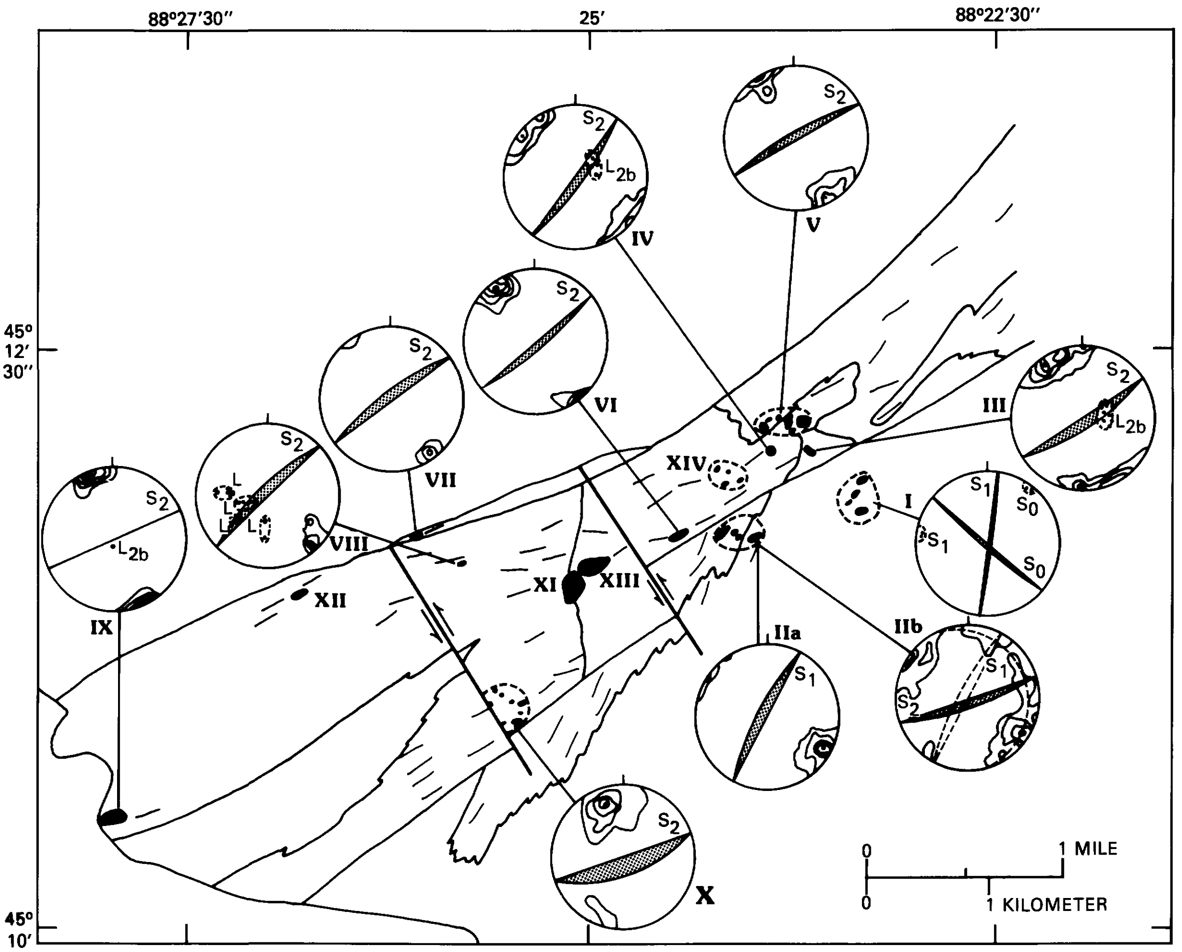

Figure 6. Generalized geologic map of study area showing lower hemisphere, equal-area stereoplots of structural data from selected outcrops. Contour intervals are variable. See text for discussion of outcrops I through XIV. Note that outcrop areas XI, XII, XIII, and XIV do not have accompanying stereoplots.

having a shallower dip than the dip of the stretch axis, as shown in figure 11. Stereoplots at localities III and IV (fig. 6) indicate a steep easterly L_{2b} stretch fabric, whereas that at locality IX indicates a steep southerly stretch fabric. This difference in orientation of stretch fabrics suggests a varying sense of movement of the shear couple along the length of the shear zone.

Field data suggest that the sense of movement in the horizontal plane was generally dextral (right lateral). At the map scale (figs. 2 and 6), S_1 foliation appears to have been rotated clockwise toward parallelism with the shear zone, which is consistent with dextral movement. Also, the granodiorite body (unit Xg) is displaced right laterally in the shear zone as granitic gneiss (unit Xgn). In addition, rare S-C fabrics observed at localities XIV (fig. 6) and VIII (fig. 9) suggest dextral movement. Such movement is supported also by measured axes of extension (L_{2b}, fig. 6) as well as by computed ellipsoid axes; these axes plunge toward the east-southeast quadrant of stereoplots, indicating that the upthrust southeast block had a dextral component of movement in the horizontal plane, as shown in figure 11. On the other hand, the variation in orientation of L_{2b} shown in figure 6 suggests a different horizontal shear sense from place to place along the shear zone. This variation is supported by a well-exposed S-C fabric in metavolcanic rocks at field locality III, which unequivocally indicates a sinistral sense of horizontal movement.

Strain Analysis

In general, rocks within the Mountain shear zone lack structures suitable for strain analysis, and only a few outcrops exist where strain could be estimated. We selected samples from three areas for strain analysis, as shown in table 2. Samples from areas IV and X (fig. 6) were selected because preliminary analysis of thin sections indicated that these rocks had domains (>½ cm in smallest dimension) that consisted primarily of contiguous deformed grains of quartz or feldspar which could be analyzed by the Fry (1979) technique. A sample

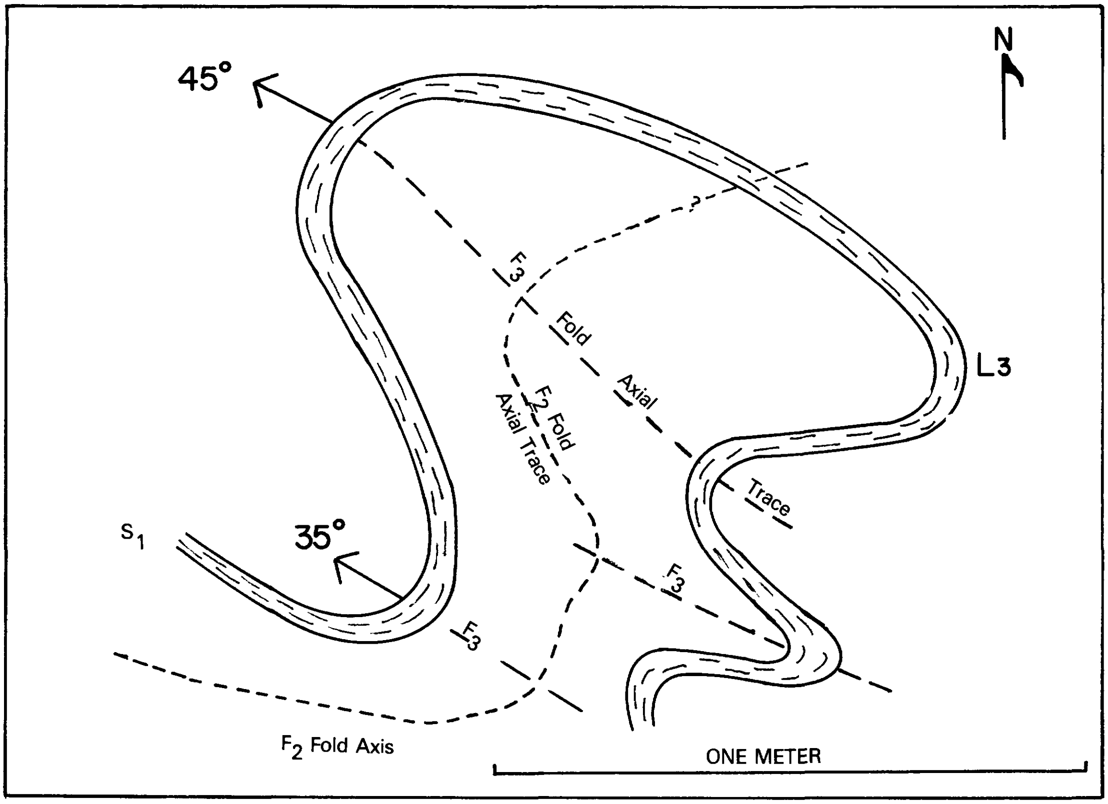

Figure 7. Field sketch of multiple phases (F_2, F_3) of deformation in granitic gneiss. S_1 foliation is parallel and has been folded during F_2 deformation as shown by the F_2 fold axial traces (L_2). S_1 and L_2 have been folded by the third (F_3) phase of deformation. L_3 fold axes trend northwestward.

from area IX contained well-exposed flattened and stretched volcanic clasts whose dimensions could be measured in the field. Lithologic descriptions of these rocks are given in table 2.

Both nature of rock and extent of our experiments influenced the results of the strain analyses: (1) Clasts and quartz grains were not spherical prior to the onset of F_2 deformation; their shape at the time of F_2 deformation reflects varying degrees of F_1 deformation. (2) The strain estimates apply only to the immediate vicinity of the analysis; we did not construct strain estimates for the more intensely mylonitized rocks. (3) Strain estimates were constructed from rocks of variable composition, as shown in table 2; it is possible that the variable amount of strain among the different rock types mainly reflects differences in physical compositions.

Method

The strain in samples from localities IV and X (fig. 6) was determined by cutting three mutually perpendicular rock slabs from an oriented field sample. Images of oriented oversized (3 cm×6½ cm) thin sections prepared from these slabs were projected onto a screen. Outlines of quartz grains were traced from quartz-rich domains in these slides. Strain ellipses for each thin section were then determined using the graphical techniques of Fry (1979). The strain for locality IX (fig. 6) was determined by measuring strain ellipse parameters in the field from strained volcanic clasts on three roughly perpendicular faces. Ratios of the principal $X>Y>Z$ axes of the strain ellipsoids were measured in the field and orientation of the long axis (stretch direction) of the strain ellipse was determined.

Finite strain was calculated using an unpublished computer program written by A.W.B. Siddans. This program calculates the ratios of the major axes of the strain ellipsoid, their orientation relative to the coordinate system used, and the Flinn (1962) K values for the ellipsoid. Siddans' program also provides a measure of the "internal consistency" of the ellipsoid parameters as determined by calculating the strain parameters from different ellipse pairs. The orientation and scatter of the principal strain axes for samples from localities X and IV are shown in figure 12*A* and *B*. These orientations are relative to an arbitrary set of coordinates used to input data into Siddans' computer program. We have rotated the axes on a stereonet to their proper position in space, as shown by the shaded areas in figure 12.

Table 2. Data on rock type and strain analyses

Outcrop	Rock description	Strain analysis approach	Percent flattening	Percent stretching	Flinn K value	Logarithmic K value	Flinn field	Internal inconsistency level (percent)
IV	Protomylonitic granite and granitic gneiss. Felsic domains as much as 1 cm in dimension are separated by anastomosing fine-grained mylonitic bands. Felsic domains contain abundant contiguous quartz and some saussuritized feldspar.	Fry analysis of quartz-rich domains on three perpendicular faces. Quartz-rich domains lie between mylonitic bands.	24.12	44.18	2.824	2.621	Apparent constriction. Volume gain.	24.29
IX	Mylonitized metavolcanic rock with numerous highly deformed biotite-rich, hornblende-bearing mafic clasts. Matrix consists of layers of clinopyroxene, plagioclase, and minor quartz. Mafic clasts are highly deformed.	Field measurement of major axes of strained clasts on three perpendicular faces.	65.62	186.28	0.930	0.956	Near plane strain. In field of apparent flattening. Slight volume loss.	24.0
X	Granoblastic rock containing plagioclase, biotite, hornblende, and minor quartz and chlorite; strongly foliated but not banded. Lithic clasts have same composition as matrix.	Fry analysis on three perpendicular faces. Used plagioclase grains.	21.04	29.54	0.922	0.914	Same as sample IX.	6.2

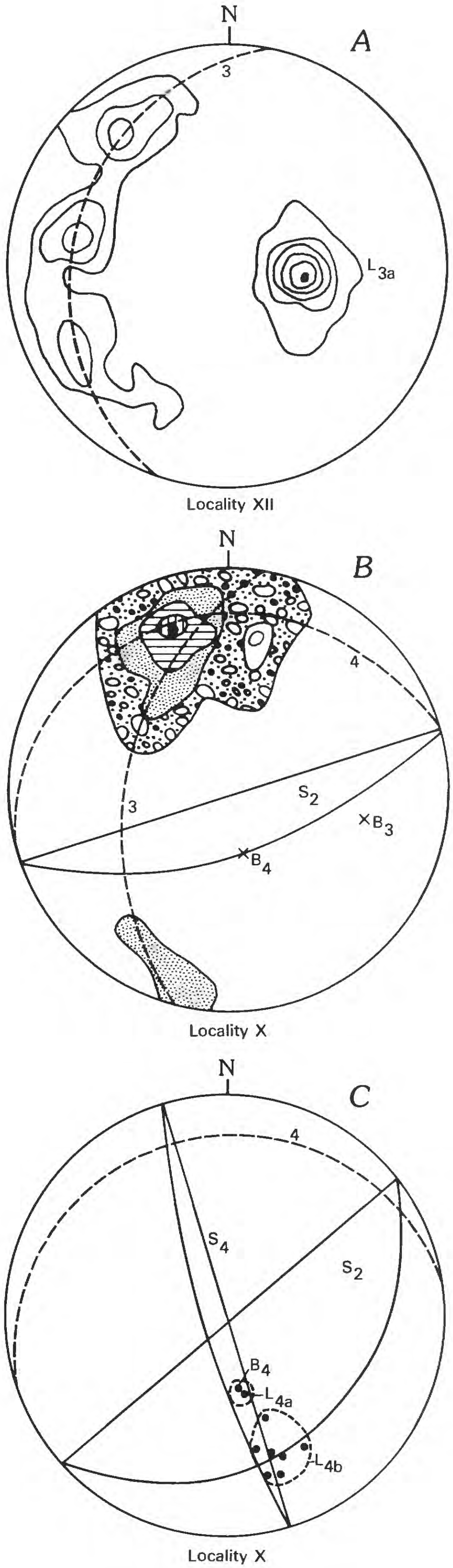

Figure 8 (facing column). Lower hemisphere equal-area stereographic plots. *A* is from outcrop XII (fig. 6), *B* and *C* are from outcrop X. *A*, Girdle 3 contours at 2, 6, and 12 percent are constructed for 50 poles to S_2 foliation; contours for L_{3a} at 2, 10, 20, 30, and 40 percent are constructed for 50 measurements of F_3 fold axes. *B*, Contours at 1, 5, 10, and 20 percent are on 72 poles to S_2 foliation; orientation of best S_2 foliation plane shown and beta axes B_3 and B_4 correspond to girdles 3 and 4 respectively. *C*, Girdle 4 and B_4 are transferred for comparison purposes from *B*. Field-measured S_4 spaced cleavage plane shown as well as S_2 foliation at small outcrop within area X. L_{4a} represents axes of F_4 folds. L_{4b} represents lineations measured in the field that formed by intersection of S_2 and S_4 foliation planes.

Results

Strain analysis of the sample from locality X (fig. 12*A*) shows good internal consistency, and the results agree well with field measurements. Samples from localities IV (fig. 12*B*) and IX, on the other hand, have poor internal consistency relative to the sample from locality X, inasmuch as the ellipse parameters determined from different ellipse pairs do not agree within 24 percent (table 2). We attribute these poor internal consistency values to inhomogeneous deformation in the sample. Strain ellipses for the sample from locality IV, for example, were determined from grains within quartz-rich domains in the mylonitic granitic gneiss. Although the ellipsoid axes determined from different pairs disagree by as much as 24 percent, and show considerable spread on stereographic plots (fig. 12), the general orientation of the computed axes is close to stretch axes measured in the field (fig. 12*C*).

Some general conclusions can be drawn from the strain analyses. The sample from locality X, which is near the southern margin of the shear zone, has a Flinn (1962) K value of 0.922, which lies very near the plane strain line, barely in the field of apparent flattening. Localities IV and IX are near the center of the shear zone. The sample from IX has a Flinn value of 0.930, also near the line of plane strain, whereas the sample from IV has a Flinn value of 2.824, clearly in the field of apparent constriction. These results suggest that the rocks in the southwestern part of the shear zone were slightly flattened, whereas rocks toward the northeast were stretched. Alternatively, the results could reflect original differences in shape and orientation caused by the earlier F_1 deformation.

Although the data on the percentage of F_2 flattening and stretching are not firm because of the relatively high internal consistency level, the unknown nature of F_1 deformation, and differences in rock types, they do suggest that strain was heterogeneous within the shear zone. The 21 percent flattening and 29 percent

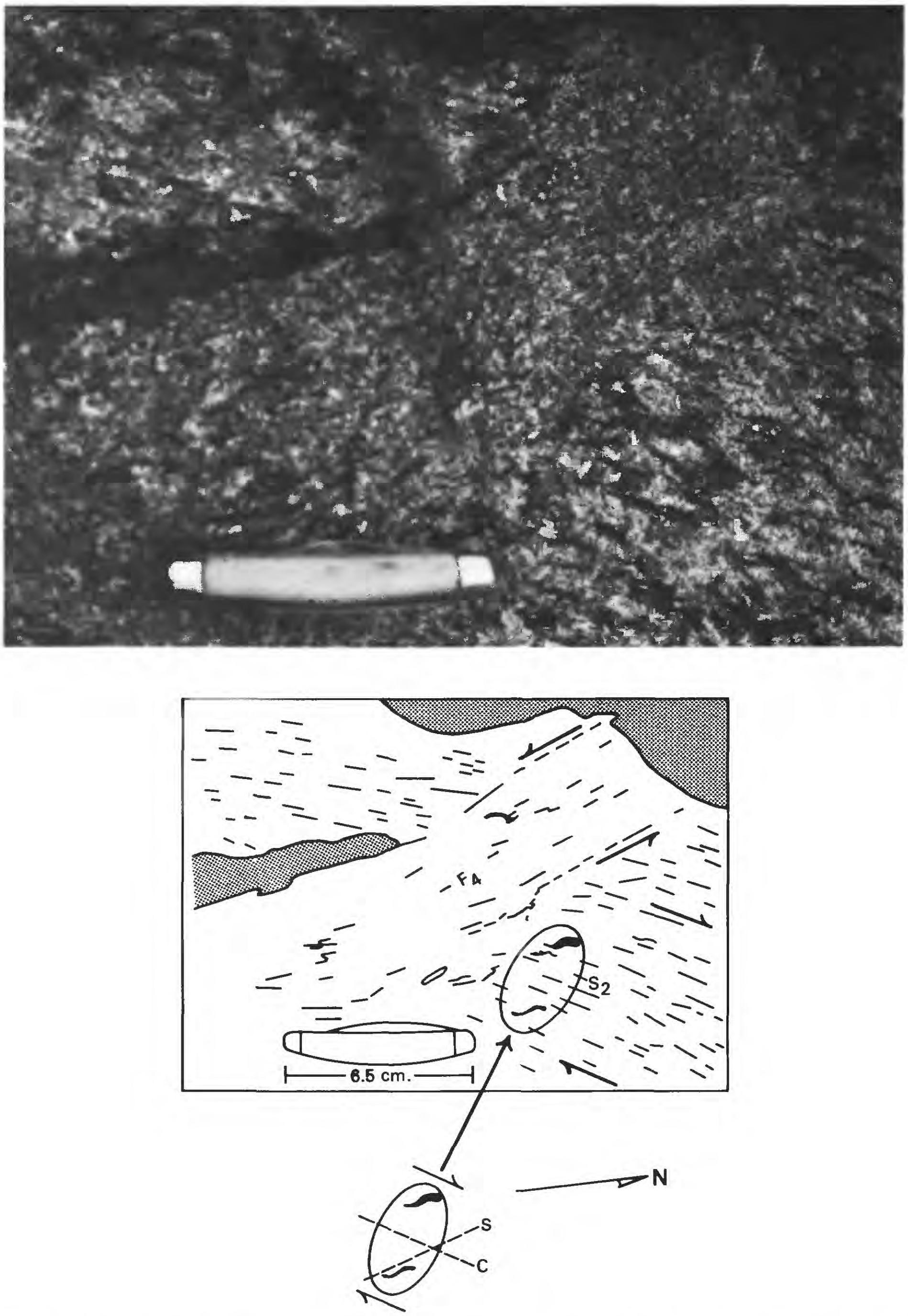

Figure 9. Photograph and sketch of narrow ductile shear zone caused by F_4 deformation at outcrop XIII (location, fig. 6). The shear zone transects strongly foliated granitic gneisses and is parallel to and related to the major sinistral fault that crosscuts the main Mountain shear zone. Inset sketch shows S-C fabric in Mountain shear zone with dextral sense of shear.

stretching values for the sample from locality X (table 2) have good internal consistency, and probably accurately represent the bulk strain in these rocks. Flattening and stretching percentages of 66 and 186 respectively (table 2) from the sample at locality IX reflect much higher strain than in samples from IV and X. This high strain is likely a function of the mafic composition of the rock. The 24 percent flattening and 44 percent stretching values for sample IV probably are minimum values because they were derived from relatively undeformed

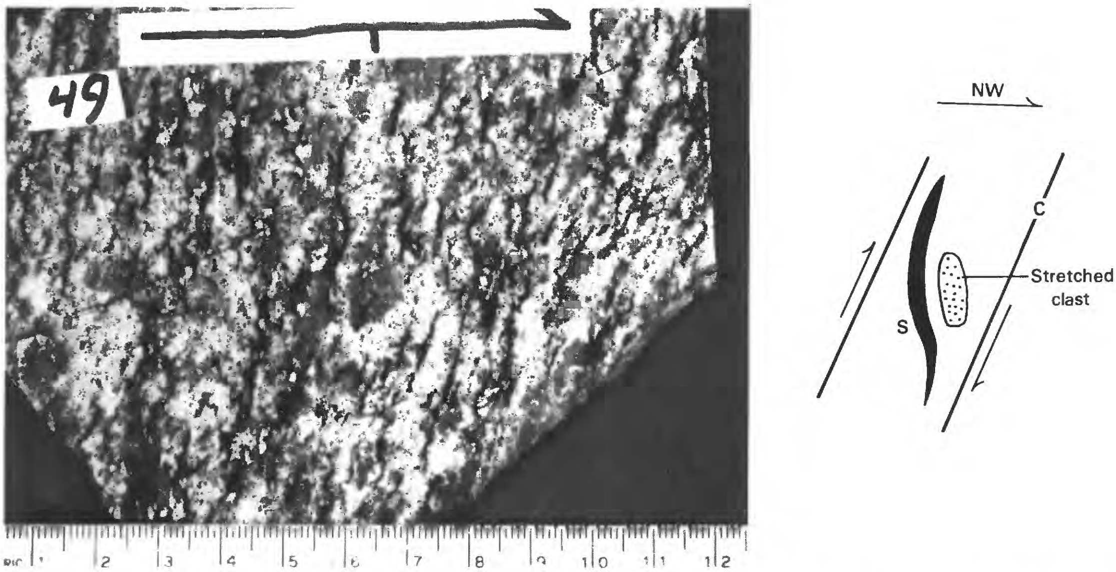

Figure 10. Photograph of granitic gneiss slab from outcrop XIV (fig. 6) showing S-C fabric viewed from the northeast parallel to the shear zone. The slab is cut so that it is vertical and strikes perpendicular to the strike of S_2 foliation. Direction of relative movement is shown diagrammatically adjacent to the photograph. The long (X) axis of the strained clast lies within the S plane of shear. Scale in centimeters.

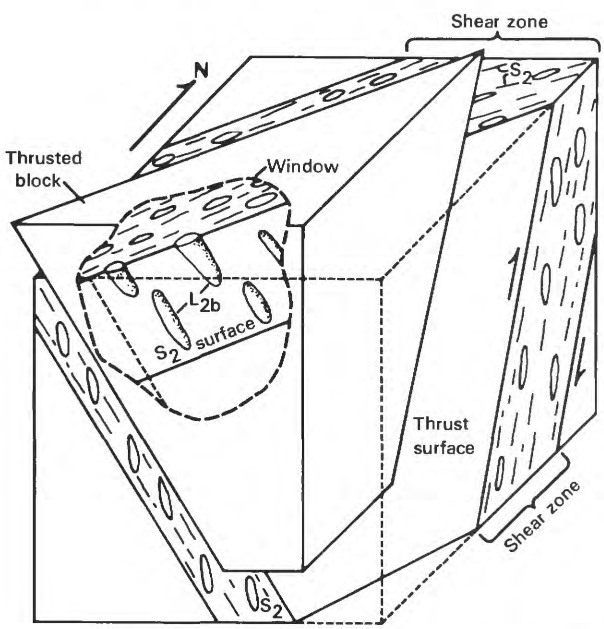

Figure 11. Block diagram showing relationship of strained clasts (strain ellipsoids) to simple shear envelope. Note that the stretch (long) axes of the clasts (L_{2b}) dip more steeply than the shear zone.

quartz-rich domains between mylonitized domains in the rock. Despite the uncertainties of the strain analyses, the results presented in table 2 suggest that rocks in the center of the shear zone are more highly strained than those along the southeast margin.

Conclusions

Rocks within the Mountain shear zone are L-S tectonites that accord with the classic definition of a shear zone (Ramsay, 1980). The shear zone is a local (discrete) linear zone of relatively high ductile deformation. Neither the width nor the length is known, but we presume that the shear zone had parallel sides prior to emplacement of the Wolf River batholith. In this area, the batholith was emplaced passively.

Ramsay (1980) classified shear zones according to their displacement fields. The Mountain shear zone appears to best fit Ramsay's (1980) type (iii) classification; that is, it is a heterogeneous simple shear with accompanying heterogeneous volume change. Ramsay and Graham (1970) noted that most deformation from natural orogenic processes leads to states of heterogeneous strain, and Ramsay (1980, p. 89) noted that "the basic component of practically all shear zones is that of heterogeneous simple shear***made up of a number of elements showing homogeneous simple shear." The Mountain shear zone has the following features that fit these criteria.

(1) Deformation within the shear zone was not uniform; domains of relatively low strain, where pre-F_2 features are preserved, as well as domains of high strain, where the country rocks have been mylonitized, are present.

(2) The nature, magnitude, and orientation of displacement vary both across and along the shear zone, as suggested by the variation in (a) shape of the strain ellipsoids at localities IV, IX, and X, (b) percentage of

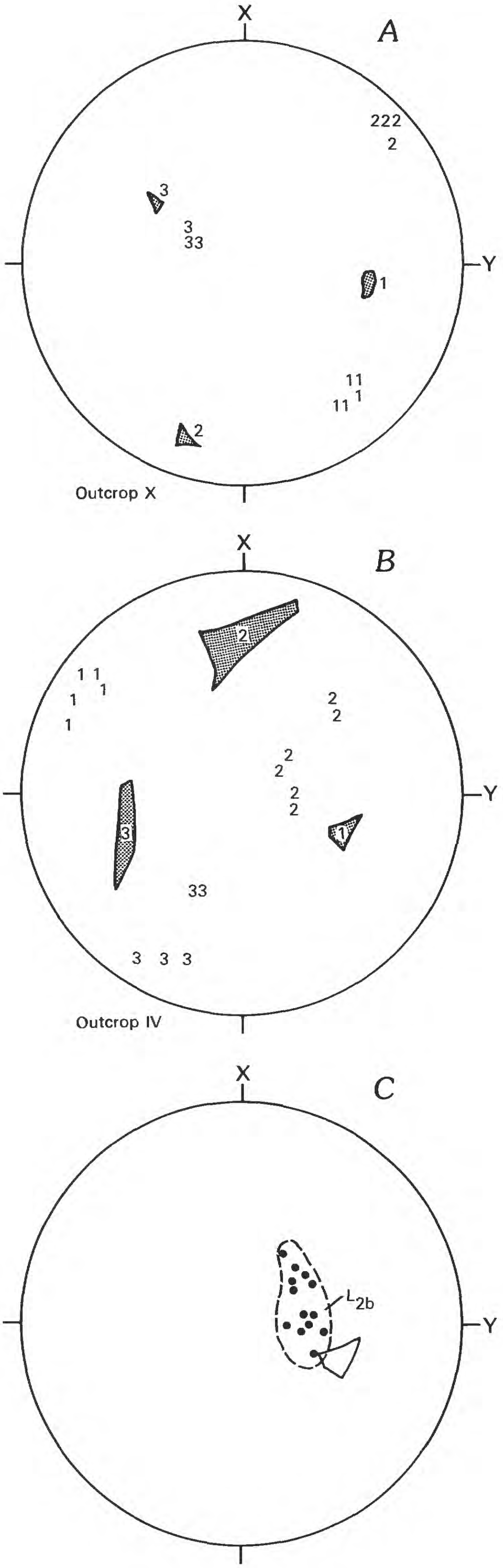

Figure 12 (facing column). Lower hemisphere equal-area stereoplots of orientation of principal strain axes of the strain ellipsoid generated by A.W.B. Siddans' program. *A* is from outcrop X (fig. 6); *B* is from outcrop IV (fig. 6). 1, axis of maximum elongation; 2, intermediate axis of elongation; 3, axis of minimum elongation. Orientations are relative to an arbitrary set of reference coordinates and must be rotated to show their true orientation in space. Shaded areas represent the correct position of the ellipsoid axes in space. *C*, Points represent orientation of long (stretch) axes of strained clasts measured in the field from localities III and IV. Small triangular area represents orientation of axis of maximum extension as determined from strain analysis of outcrop IV.

flattening and stretching among the three outcrops where strain analyses were carried out, and (c) movement pattern along the shear zone; the orientation of the maximum principal shortening direction apparently rotated from nearly west in the northern part of the exposed shear zone (localities III and IV, fig. 6) to north-northwest at its southwestern exposed segment (locality IX, fig. 6), as indicated by the orientation of deformed clasts (L_{2b}).

(3) L-S tectonites of the shear zone appear to have formed primarily by plane strain, as indicated by Flinn K values at localities IX and X that are very close to 1, the value for plane strain. Rocks at locality IV, however, have a K value of 2.4, indicating that they lie in the field of apparent constriction.

(4) As shown in table 2, the logarithmic or natural strain K values (Ramsay, 1967) suggest that rocks at outcrops IX and X underwent only minor volume loss, whereas those at outcrop IV underwent appreciable volume gain.

(5) The magnitude of both flattening and stretching increases from the southeast margin of the shear zone toward the center.

(6) Finally, Roy (1977) has pointed out that mylonites within shear zones develop in stages and that this development is accompanied by chemical mobility. Chemical mobility is suggested in the Mountain shear zone by an apparent substantial gain in modal quartz of the granodiorite gneiss (Xgn unit) within it, as compared to undeformed granodiorite (Xg unit), but this apparent gain has not been confirmed by chemical studies.

REGIONAL SIGNIFICANCE

Prior to this study, major northeast-trending shear zones in the Wisconsin magmatic terranes were known to have formed subsequent to the main regional deformation (Sims and Peterman, 1983, p. 8), but data on the precise timing were lacking. The fortunate existence of a datable intrusive rock (Hines Quartz Diorite, 1,812.7±3.6 Ma) within the Mountain shear zone, which apparently was emplaced near the end of the ductile deformation and thus establishes a firm younger limit for the shearing, provides a benchmark for the time of shearing on a regional basis. Thus, it can now be presumed that the steep Jump River and Athens shear zones (fig. 2) as well as others of N. 50°–60° E. trend have comparable ages (Sims and others, in press). A deformed intrusive rock within the Athens shear zone, which has a crystallization age of 1,832±9 Ma (Sims and others, in press) is consistent with this interpretation that the shearing postdates 1,840 Ma. The recognition of a major ductile deformation event 25 to 35 m.y. after the main collisional event (≈1,850 Ma; Sims and others, 1985) indicates the complexity and long duration of tectonic events in the Penokean orogen and the need to identify specific events, perhaps by assigning names to them, such as has been done in the Wopmay orogen in the Northwest Territories (Hoffman and Bowring, 1984). It seems improbable, however, that the ≈1,815 Ma ductile deformation could be a late tectonic episode related to the collision that sutured the Wisconsin magmatic (arc) terranes to the continental margin at about 1,850 Ma. Instead, we suggest that the ≈1,815 Ma ductile deformation possibly resulted from a continent-continent or continent-arc collision far removed from northern Wisconsin, probably to the south or southeast.

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