

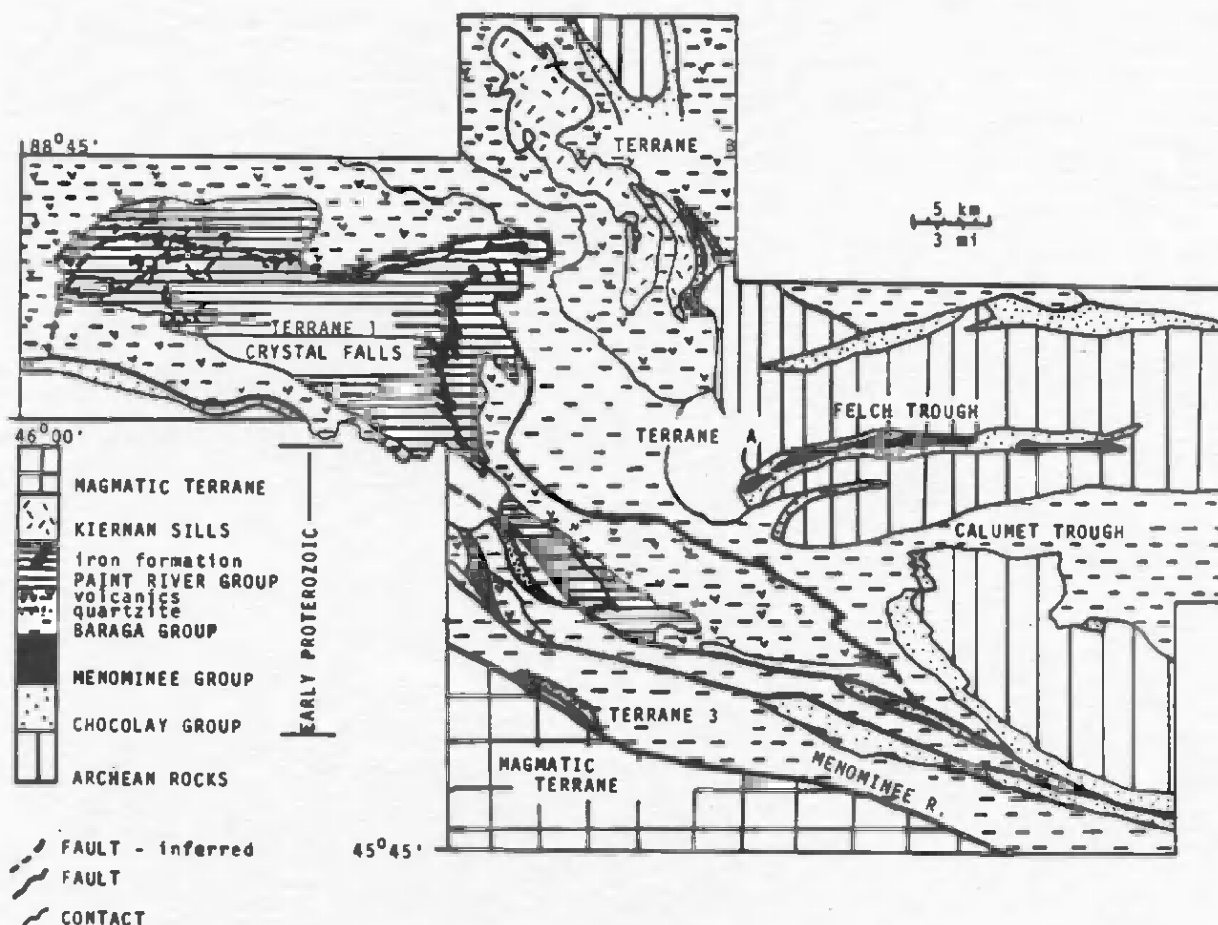
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FIELD TRIP 2

EARLY PROTEROZOIC TECTONOSTRATIGRAPHIC TERRANES OF THE SOUTHERN LAKE SUPERIOR REGION: FIELD TRIP GUIDE WITH SUMMARY



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Early Proterozoic Tectonostratigraphic
Terranes of the Southern Lake Superior Region:
Field Trip Guide with Summary

Field Trip Leaders

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TERRANES OF THE SOUTHERN LAKE SUPERIOR REGION:
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INTRODUCTION

Geologic studies in the Lake Superior region underwent a minor revolution in 1976 with the publication of Van Schmus' paper summarizing the geology and speculating about early Proterozoic tectonics of the Great Lakes region. Van Schmus proposed that a belt of calc-alkaline magmatic rock extending across northern Wisconsin represented the exhumed remnants of an Andean-type arc which had formed on an older passive margin, exposed to the north (Fig. 1). Cambray (1978), Larue and Sloss (1980) and more recently Greenberg and Brown (1983) proposed instead that an arc terrane collided with a passive continental margin about 1.8-1.9 b.y. ago.

The present paper relies on a previous study recently published (Larue, 1983) concerning the geology of the southcentral to southeast Lake Superior region. Previously one of us suggested (Larue, 1983) that early Proterozoic rocks of the Lake Superior region can be described in terms of a number of discrete terranes (Fig. 1, 2) including: a miogeocline (terrane A,B), a probably composite magmatic terrane (mt) (Laberge and Meyers, in press) and two smaller, complicated terranes composed of miogeoclinal lithologies, the Florence-Niagara and Crystal Falls terranes (Fnt, Cft). In Larue (1983), it was suggested that the

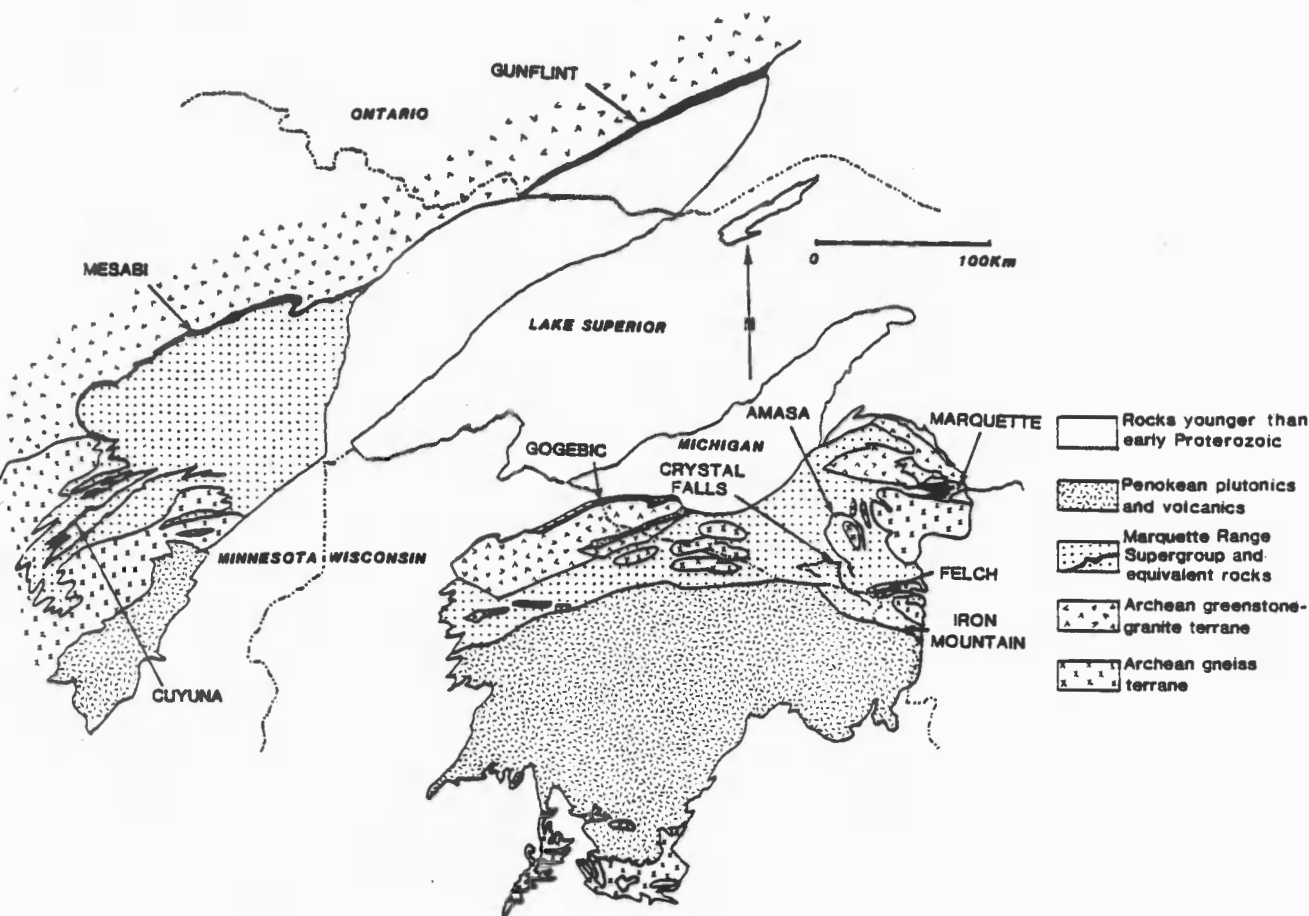


Fig. 1 A. Location of the Lake Superior Region. (After Morey, et al, 1982)

mt represents an arc terrane that collided with and probably overthrust the miogeocline, and that the CFT and FNT were also probably emplaced during this major accretion event. The fault that separates the mt and the terranes composed of miogeoclinal lithologies is known as the Florence-Niagara fault, and may represent a suture.

The present paper is aimed at discussing the following points: 1) a brief review of the geology of the southern Lake Superior region; 2) recent studies that we have made in the southern Lake Superior region astride the Florence-Niagara fault. Specifically, we present data concerning structural evolution of the area surrounding the suture. We will stress the complicated nature of

this deformation by examining the structural history of each terrane. In addition, we present some new exciting data on the geochemistry of early Proterozoic shales in the Lake Superior region. We begin with a discussion of lithologies in the southern Lake Superior region, followed by a structural analysis and summary. We do not attempt to modify existing tectonic models in this paper.

The responsibilities for work are as follows: W.L. Ueng, regional deformation model; D.K. Larue, regional studies; R.L. Sedlock, deformation in magmatic terrane; D. Kasper, geochemistry. These studies were supported by the National Science Foundation (NSF EAR 80-08202, 81-08564) to D.K. Larue and by the U.S. Geological Survey.

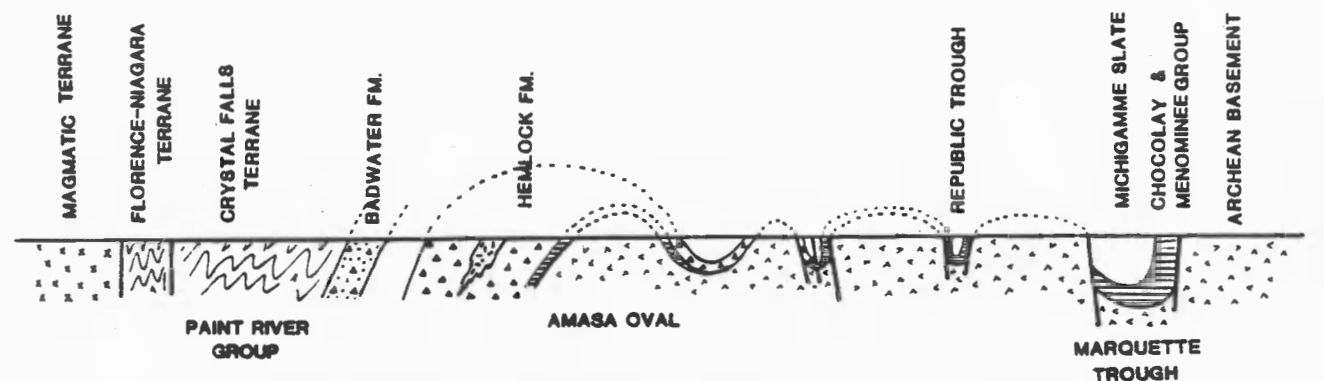


Fig. 1 B. Idealized NW-SE cross section of Florence Niagara and Crystal Falls terranes located in Fig. 2.

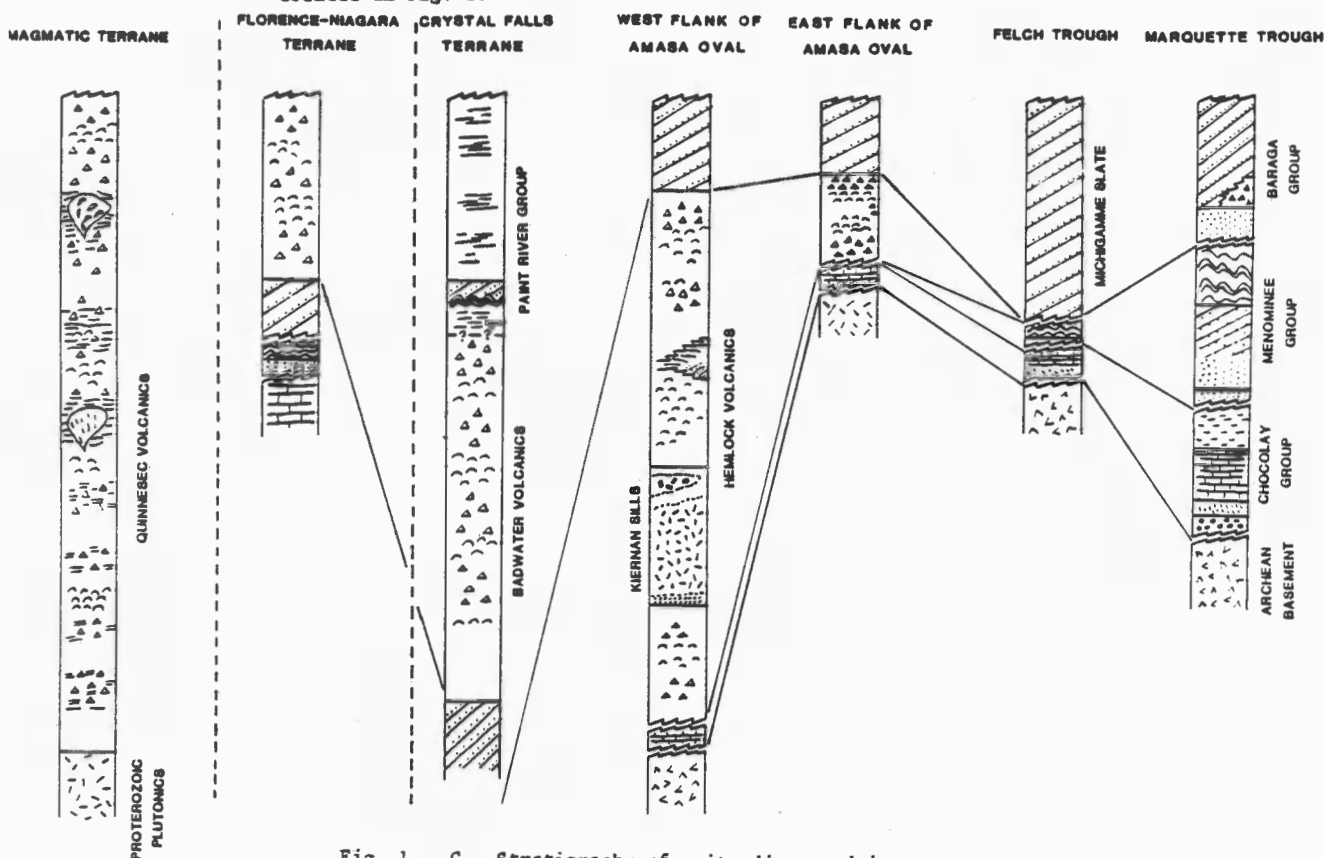


Fig. 1 C. Stratigraphy of units discussed in text.

GEOLOGY OF THE MIOGEOCLINE

General

Older Precambrian Basement. Older Precambrian basement shown in Figure 2 is exposed only in the miogeocline, and can be divided into two types: Huronian strata (2.2-2.3 b.y.) and Archean (>2.4 b.y.) crystalline rocks (Van Schmus, 1976). Huronian strata are relatively rare in the Lake Superior region (Van Schmus, 1976) and are not discussed here. Morey and Sims (1976) divided the Lake Superior region Archean rocks into a younger (2.7-2.5 b.y.), northern, granite-greenstone terrane and an older (>3.0 b.y.), southern, gneissic terrane (Fig. 1). Archean rocks in Figure 2 are in their gneissic terrane.

Marquette Range Supergroup. The Chocoy Group unconformably overlies older Precambrian basement, consists of basal conglomerate overlain successively by quartzite, dolomite, and slate and is the lowermost unit of the Marquette Range Supergroup (Fig. 2B).

Menominee Group strata rest unconformably on Chocoy Group strata, and consist of quartzite or muddy quartzite overlain by banded iron formation (Fig. 2B). The Baraga Group overlies the Menominee Group at least locally unconformably, and consists of dominantly deep-water sandy and muddy turbidites and volcanic units.

Subterrane A

The miogeocline is divided into subterrane A and B (Fig. 2), which have different geologic features but are not separated by any apparent major structural discontinuity.

Boundaries and Distinguishing Features.

Subterrane A is inferred to be fault-bound on the west with the CFT and fault-bound on the south with the FNT, is overlain to the east by Phanerozoic cover, and is apparently continuous to the northwest (subterrane B) and to the north. Subterrane A is unique with regard to the other terranes discussed here because it lacks the thick sequence of Baraga Group volcanics of the CFT and subterrane B, and significant mappable units in the Baraga Group composed of mature (quartzose and carbonate) lithologies as in the FNT.

Stratigraphy. The oldest Proterozoic rocks of subterrane A are those of the Chocoy Group, which include locally thick accumulations of quartzite and dolomite. Muddy quartzites and iron formation of the Menominee Group unconformably overlie strata of the Chocoy Group and are relatively thin. Baraga Group slates and dirty sandstones, locally with volcanoclastic interbeds (James and others, 1968), cap the sequence.

Larue and Sloss (1980) and Larue (1981a) have suggested that the Felch and Menominee structural troughs were sedimentary basins during Chocoy Group sedimentation. This interpretation is based on the presence of trough-parallel paleocurrent vectors from cross-beds in quartzite in the areas within the structural troughs. The Felch basin was bound on either side by platforms, now expressed by exposed Archean basement. Archean basement is present only on the northeast side of the Menominee trough. The southwest margin of the Menominee

trough is structurally complicated and not well understood. In fact, this side of the basin may have been open, such that the Menominee basin may have had only one well-defined margin.

During Menominee Group sedimentation, the Felch and Menominee basins received little sediment. Apparently, the basins became inactive during this period, and it is not known whether these basins were reactivated during Baraga Group sedimentation. The complex structural and metamorphic overprinting of these strata precludes detailed sedimentologic analysis. Baraga Group sediments represent products of regional deep-water sedimentation.

Subterrane B

Miogeoclinal subterrane B is different from subterrane A because it contains much greater volumes of early Proterozoic mafic igneous rocks.

Stratigraphy. The basement of subterrane B is Archean gneiss which forms the core of a large dome, the southern tip of which is shown in Figure 2A. Marquette Range Supergroup strata mantle the dome. Chocoy Group dolomites comprise the lowermost part of the sedimentary drape, and are overlain by Baraga Group volcanics and sediment. Of particular interest is the Kiernan sills intrusive complex which is of greatest thickness to the southwest of the domes (Fig. 2B) but is probably equivalent to scattered, smaller mafic intrusions that occupy a similar stratigraphic position around the perimeter of the dome (Cannon, 1978). Where it is thickest, the Kiernan complex consists of: 1) a cumulate-layered ultramafic rock base (100-300m); 2) a cumulate and isotropic gabbro medial section (1-3 km); and 3) a pillow basalt cap (>1 km) overlain by ribbon cherts and turbiditic ash beds (~100 m), and iron formation (the Mansfield member; ~200 m) (descriptions from Gair and Weir, 1956; Bayley, 1959; Weir, 1967). The Kiernan complex probably originated as the floor of a volcanic basin within continental crust, during deposition of Baraga Group strata (Fox 1982; Wilband and others, in prep.).

Crystal Falls Terrane

Boundaries and Distinguishing Features. The CFT is roughly equidimensional in shape and is inferred to be fault-bound. The CFT is in fault contact on the south with the FNT (Fig. 2A). An inferred fault to the east separates the CFT from terrane A, and an inferred fault to the north separates the CFT from terrane B (the latter two fault boundaries are inferred based on truncation of aeromagnetic trends shown on the map by Zietz and Kirby, 1971). There is insufficient outcrop to define the exact boundaries of the southwest and west sides of terrane 1; however, faults are inferred based on preliminary study of aeromagnetic anomalies.

Stratigraphy. No unequivocal Chocoy or Menominee Group rocks are present in the CFT. Baraga Group extrusive volcanics (Badwater-Greenstone) are in fault contact with Chocoy Group strata of the FNT in the SW of the CFT. Presumably deep-water turbiditic sandstones and pelites of the Paint River-Group unconformably(?) overlie Baraga Group strata (James and others, 1968). A deep-water (below storm-wave base) origin

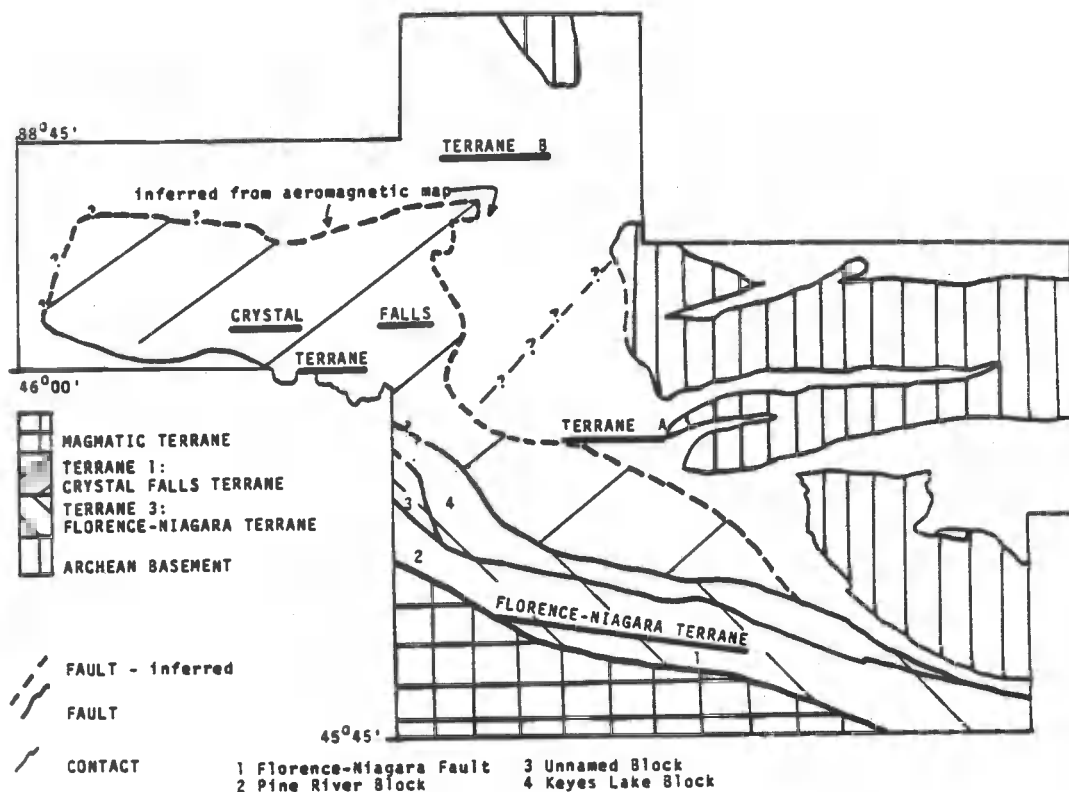


Fig. 2 A. Terranes in the south central Lake Superior region. After Larue (1983).

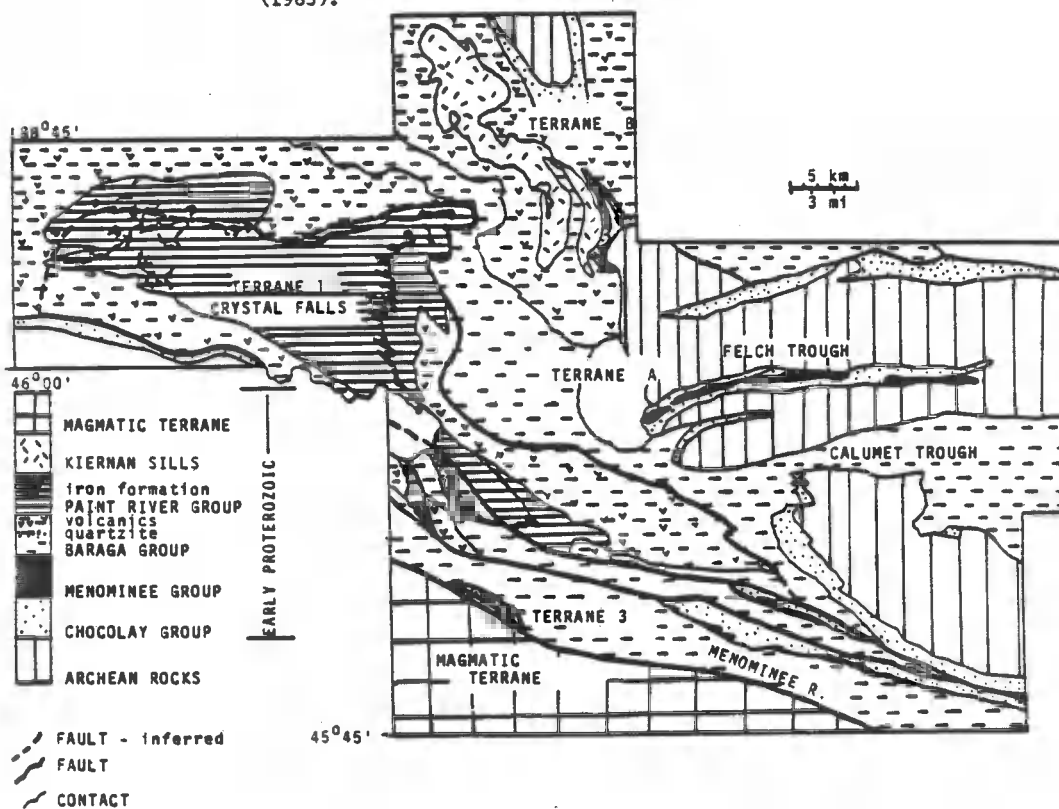


Fig. 2 B. Terrane map of Fig. 2A with geology superimposed.

is proposed because of the fine-grained, thin-bedded nature of these rocks; their significant lateral extent without evidence of interfingering with shallow-water deposits; and their significant formation thicknesses within sequences that show no evidence of shallowing.

The Florence-Niagara Terrane

Architecture. The FNT is at least 40 km long and consists of a number of major steeply-dipping faults that separate disparate lithologies and offset metamorphic isograds (Bayley and others, 1966; Dutton, 1970). Four of these major faults in the FNT define three composite fault slices with cumulative width of about 5-8 km; the Pine River, the Keyes Lake and an intermediate unnamed block called the Bessie Babbit block by Larue and Ueng (submitted) (Fig. 2A). As will be shown in the structure section, these three blocks are composed of additional fault slices and thus are composite.

The Pine River block contains Choccolay, Menominee and Baraga Group strata. The Baraga Group comprises the Michigamme Slate in the Pine River block, and consists mainly of pelites, of probable deep-water origin, and a fault-bound unit of 0.5 km thick of pebbly quartzite representing shallow-water or fluvial deposition.

The intermediate fault slice is poorly exposed, and contains Paint River Group strata and pillow basalts of the Badwater Greenstone which are folded in a SE-closing syncline (Dutton, 1970). The Paint River Group in this intermediate block contains two principle lithologies, iron formation and slate with thin graded sandstone interbeds. Dutton (1970, plate 5) shows that the southwestern fault that defines the unnamed block truncates metamorphic isograds, demonstrating the movement on the fault occurred after regional metamorphism.

The Keyes Lake block is similar to the Pine River block, containing Choccolay, Menominee and Baraga Group strata. Michigamme Slate of the Baraga Group includes another fault-bound unit 0.3 km thick quartzite representing shallow marine or fluvial deposition, also studied by Nilsen (1965). Pillow basalts of the Badwater Greenstone (Fig. 2B) are present in this block in the west part of the Florence County Quadrangle.

Magmatic terrane

In the magmatic terrane, granitoid and gneissic rocks of Penokean age are mantled by highly deformed units of three major lithotypes: 1) a schistose suite, consisting of felsic to predominantly mafic metavolcanic rocks of the Quinnesec Formation (Bayley and others, 1966); 2) a metasedimentary rock suite, consisting of scattered outcrops of quartzite and slate; and 3) a gabbroic suite, which includes pillowed and massive basalt, massive gabbros of varying composition, and local diabase dikes. The granitoid and gneissic rocks that form the core of the magmatic terrane have been shown by Schulz (1983) to have calc-alkaline affinities, suggesting a magmatic arc origin. The volcanic rocks of the schistose suite bear geochemical signatures typical of arc environments (Cudzillo, 1978). The gabbroic suite may be interpreted as the roots of this arc complex. Archaean gneiss present in southcentral Wisconsin (Fig. 1A) is not considered here.

STRUCTURE

Miogeocline and Crystal Falls Terrane

Structural features of Early Proterozoic rocks in the miogeocline and CFT north of the FNT are generally oriented E-W except at the Amasa Oval, Smith Creek Uplift, Kiernan Sills, and eastern margin of the CFT (Fig. 3). Most structural troughs in the miogeocline are oriented E-W, such as the Marquette trough, Felch trough, and Calumet trough. The Sagola structural basin, however, bends toward the WNW and becomes parallel to the Smith Creek Uplift and Amasa Oval. The penetrative foliation formed during the first deformation (see below) in this region which commonly strikes WNW, also bends toward the NNW and becomes parallel with the axis of the Amasa Oval. Transverse to these structural bends, tectonolithologic assemblages change in the miogeoclinal assemblage: most significantly, the amount of volcanic material in the Baraga Group increases dramatically to the W-SW across the Amasa Oval (from subterrane A to B).

Five phases of deformation have been recognized in the miogeocline, CFT, and FNT of the southern Lake Superior region based on cross-folds and cross-cutting cleavages (deformation in the FNT is considered in detail below) (Fig. 3). Four of these phases are characterized by steeply dipping cleavages and axial planes of minor folds. These deformation fabrics are recognized regionally in the area north of magmatic terrane. The other phase of deformation, F3, is defined by subhorizontal crenulation cleavages which generally dip less than 35 degrees. This set of subhorizontal crenulation cleavage is recognized everywhere but in the Crystal Falls terrane.

F1, the earliest and most pervasive deformation, is characterized by the following planar structures: slaty cleavage, schistosity, and axial planes of minor folds. In spite of later deformations, axial planes of minor folds and foliations of this deformation, S1, regionally strike N70W and dip vertically (for example, Fig. 6A, from Larue, 1983). Only in the neighborhood of the Amasa Oval, Kiernan Sills, and SE part of the CFT have S1 surfaces been passively rotated by F2 to an orientation of NNW. Apical angles of F1 folds are characteristically tight, less than 60 degrees, and fold profiles can commonly be categorized into type 1B, 1C, and type 3 folds of Ramsay's classification scheme (1967). Apical angles of these NNW-trending F1 folds are usually extremely small such that isoclinal folds and transposed layers are not uncommonly present. The foliation, which ranges from a closely spaced penetrative alignment of platy minerals to a spaced foliation or cleavage, commonly parallels bedding, especially in the limbs of isoclines.

The F2 deformation refolded the S1 surfaces and formed a set of crenulation cleavages and open folds. Axial planes and crenulation cleavages, S2 of F2, strike consistently N65E throughout the region (Fig. 3), indicating that later deformations failed to regionally refold F1 and F2 structures. Fold axes of F2 minor folds form a great circle distribution on stereogram because the F2 deformation represents folding of an already folded surface. Apical angles are commonly 70 degrees to 120 degrees, and fold profiles indicate type 1B and 1C folds. Depending on host rock lithology,

crenulation cleavage of F2 ranges from a zonal cleavage in pelitic rocks to discrete, discontinuous cleavage in metavolcanics or sandstones. In places, F2 deformation folds S1 foliations into minor chevron folds or kinks. The deployment of F2 deformation fabrics is not homogeneous throughout the area studied. F2 minor folds were observed only in the CFT and the Hemlock Formation slates above the Kiernan Sills. The development of F2 crenulation cleavages is also most intense when S1 surfaces are oriented NNW.

The F3 deformation is characterized by subhorizontal crenulation cleavages (dips < 35 degrees) which intersect with S1 foliations to form abundant subhorizontal crenulation lineations. These subhorizontal cleavages dip away, on all sides, from the Amasa Oval and the Peavy Pond intrusive. These subhorizontal foliations indicate subvertical shortening, probably associated with

basement uplift. The relation between this phase of deformation and basement is best illustrated by the case of the Peavy Pond intrusive (Fig. 3). The subhorizontal crenulation cleavages dipping away from the Peavy Pond stock can reasonably be related to the emplacement of the Peavy Pond intrusive. So it is reasonable enough to believe that the presence of subhorizontal crenulation cleavages dipping away from Amasa Oval is also the result of Archean basement uplift even though this uplift was not accompanied by any detectable thermal activity. In the Felch trough, Calumet trough and Taylor mine, the subhorizontal cleavages may also be related to mobilization of crystalline basement. But in these areas, it is difficult to pin down the exact piece of basement involved. This phase of deformation can be subdivided into different sets of subhorizontal crenulation cleavages based on which part of basement uplift

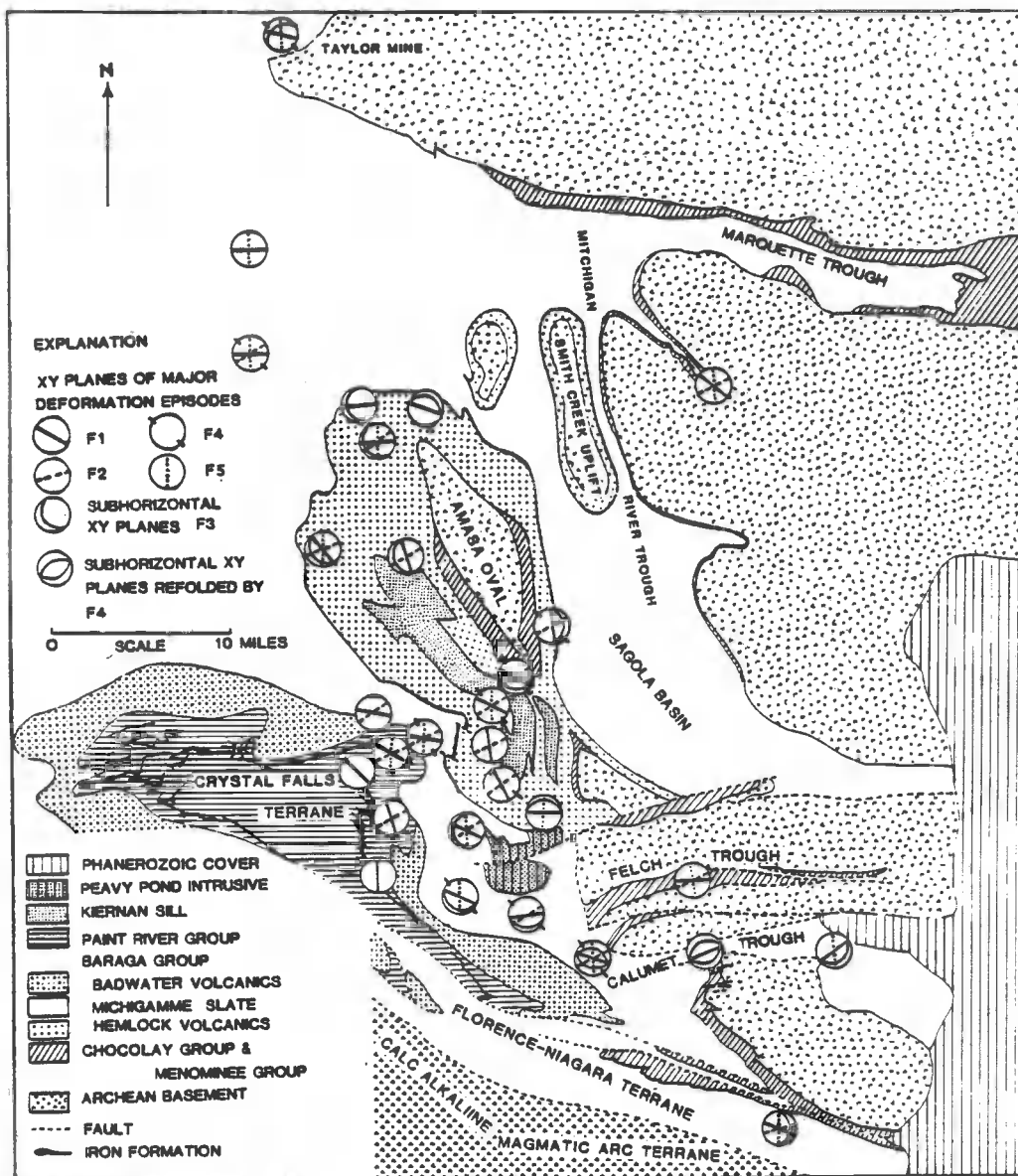


Fig. 3. Deformation in the miogeocline, Florence-Niagara and Crystal Falls terranes.

that each set is related to. However, cross-cutting relations among cleavages indicate that the time slot for formation of these subhorizontal cleavages was confined between deformations, F2 and F4. Therefore it seems that Archean crystalline basement of the study area was regionally remobilized, except in the CFT (where no crystalline basement is exposed), during this phase of deformation. Subhorizontal cleavage in the FNT is problematic, but may also be related to this period of regional uplift.

The F4 deformation is marked by sporadic occurrences of NW-striking, steeply dipping minor fold axial surfaces, kink, and crenulation planes, which cross-cut preexisting fabric. The solid evidence of this deformation is shown by refolding or crenulating F3 subhorizontal crenulation cleavages. F4 minor folds observed in the field have apical angles ranging from 70 degrees to 120 degrees.

F5 deformation is represented by a set of steeply-dipping NS-striking crenulations and some open folds with apical angles greater than 100 degrees. Fold profiles indicate that most of F5 folds are type 1B and 1C folds. Crenulation cleavages of this deformation range from a zonal crenulation cleavage to discontinuous, discrete cleavage and is commonly present whenever the S1 surfaces are oriented EW.

In spite of the fact that five phases of deformation were recognized in this region, only the first two episodes of deformation F1, and F2, were effective in constructing the regional structural features. The extremely intense NNE-SSW oriented shortening regime of F1 constructed a series of WNW trending tight folds and shear zones which sometimes involved Archean basement such as the Amasa Oval, and Smith Creek Uplift. The F2 deformation crossfolded the existing F1 structural

features and locally rotated them into NNW trending structures. The crossfolding origin of Amasa Oval instead of gneiss doming is supported by the following observations:

1. The fact that structures in strata of the Marquette Range Supergroup mantling the Archean basement of the Amasa Oval indicate crossfolding.
2. A set of penetrative NNW trending subvertical foliations, which is pervasively developed in the sediments mantling the basement, is found to be cross-cut by later deformation fabrics S2, S3. Both the cross-cutting relations and the correlation with NNW trending F1 folds in Crystal Falls terrane indicate that this is a set of rotated S1 foliations.
3. The same set of NNW trending foliations is the most prevalent foliation developed in Amasa Oval Archean basement.
4. Lack of metamorphic aureol related to Amasa Oval discredits the possible origin by gneiss doming.
5. The subhorizontal crenulation cleavage which was related to basement uplift cross-cuts the NNW trending S1.

The presence of S3 subhorizontal cleavages in this region indicates that basement uplift presided over the miogeocline once. However, the major structural features in this region were constructed mainly by periods of horizontal shortening prior to basement uplift.

Florence-Niagara Terrane

The Florence-Niagara terrane consists of at least eight fault-bound slices striking NW (Bayley and others, 1966; Dutton, 1970; Larue and Ueng, in prep.) (Fig. 4). Recognition of faults is based on truncation of regional stratigraphy (Fig. 2A) (Bayley and others, 1966; Dutton, 1970), changes in structural style or fabric across lithic boundaries, and stratigraphic relations (Larue and Ueng, in prep.), as discussed below. Fault slices 3, 7 and 7A are defined on the basis of stratigraphy each represents shallow-marine to fluvial quartzites contiguous on both sides with apparently deep-water, volcanogenic slates (Larue, 1983). Contacts are sharp, though no obvious

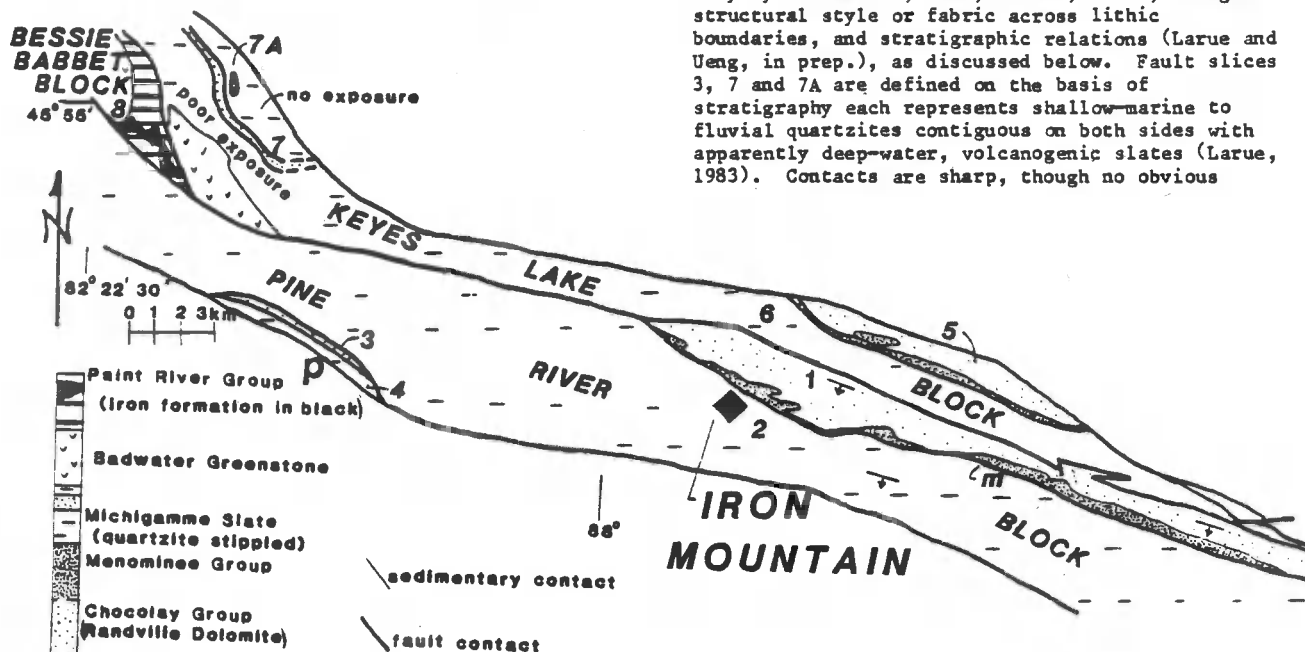


Fig. 4. Geology of the Florence-Niagara terrane.

truncations are present. All fault packets except packet 8 contain homoclinal south-facing strata. Packet 8, the Bessie Babbitt block, contains a major fold.

Four different types of structural fabric are recognized in the Fnt. All are characterized by S1, a dominant cleavage, or by axial surfaces that strike W-NW and dip steeply. Elongation lineations associated with such foliations plunge down dip in all cases except in packet 1, where bulk extension locally parallels shallowly-plunging fold axes, a probable product of superimposed strains (compaction and tectonic). 1) Fold axes in packets 1 and 5 are subhorizontal or shallowly plunging, and trend E-W to NW-SE. 2) Fold axes in packets 2 and 7A are girdled in a NW-SE plane (Fig. 6B).

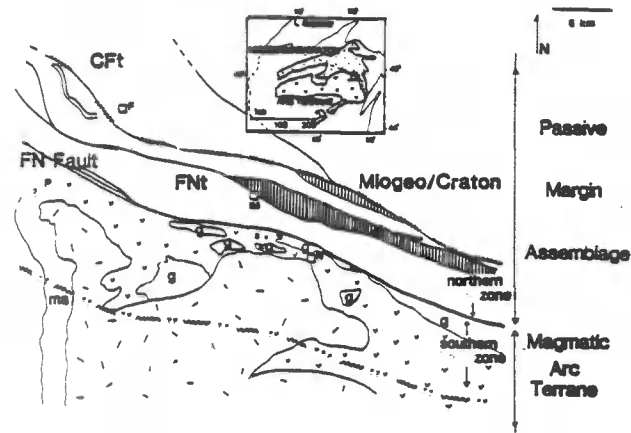


Fig. 5. Geologic map of early Proterozoic rocks near Iron Mountain (IM), MI, Florence (F), WI, and Niagara (N), WI. Florence-Niagara (FN) Fault separates passive margin assemblage to the north (Miogeo/Craton - autochthonous sedimentary cover of Superior Province basement; Fnt = Florence-Niagara terrane; Cft = Crystal Falls terrane) from magmatic arc terrane (mt) to the south (stipples - granitoids and gneiss; ms - metasedimentary rocks; g = gabbroic suite; v = metavolcanic schists). Jagged line bounds high strain belt developed on either side of the fault; queried line denotes tentative location of boundary. Solid lines bounding passive margin terranes and within Fnt are faults; solid lines in mt are lithologic contacts (after K. Schulz and P. Sims, unpub. map) that may also be faults. s = locations of slickenside striations used in stress axes calculations (see text). Vertically lined pattern denotes low-strain fault slices in Fnt.

3) Fold axes in packets 3, 4, 6, and 7 are steeply inclined and plunge down the regional foliation. 4) Fold axes in packet 8 also plunge steeply but have been complicated by cross-folds with N-S axial planes. The first three fabrics (1-3) are interpreted as products of different strain histories. The girdled fold axes (fabric 2) represents the highly strained equivalent of the first fabric type (for example, Sanderson, 1973). That is, initially subhorizontal fold axes

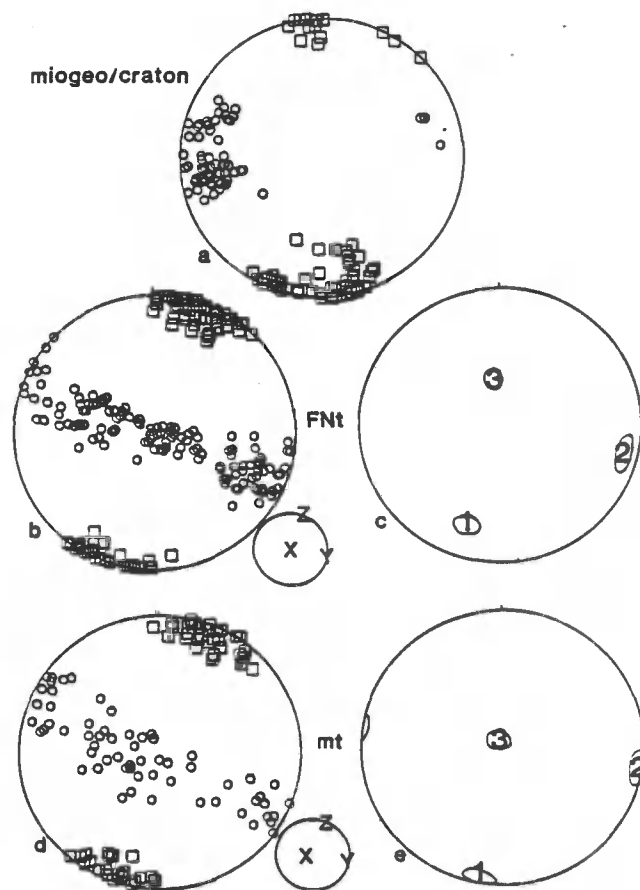


Fig. 6 6a-e. Lower hemisphere stereographic projections of structural data for D1 (accretion-related) deformation. Circles = fold axes; squares = poles to axial surfaces; 1, 2, 3 are axes of the stress ellipsoid; X, Y, Z are axes of strain ellipsoid. a. miogeo/craton folds; b. Fnt folds with inferred X, Y, Z strain axes; c. Fnt stress axes from slickenside striations with inferred 95% confidence circles; d. mt folds; e. mt stress axes.

(parallel to the intermediate axis of strain) have been strained toward the direction of finite extension. Fold axes parallel to the intermediate axis of strain rotate less than those askew, thus a girdled distribution results. The origin of fabric type 3 is poorly understood, but measured strains indicate X/Z ratios of up to 10, and therefore the fabric is also related to large strains.

Fabric 4 seems represented in fabric 3 with a superposed deformation about a N-S axial plane (S2). Minor folds with N-S axial planes are not present elsewhere in the Fnt. Crenulations with axial surfaces parallel to those described in the miogeocline (F2-F5) are present sporadically, but age relations can not be specified other than post-S1.

Metamorphism was relative complicated in the Fnt. Early folding was not associated with

significant metamorphism. Cross-folds in packet 8 pre-dated garnet grade metamorphism. Strike-slip faulting (NW-striking) with associated garnet grade metamorphism is observed in packet 4.

Slickenside striations on faults were studied (see in Fig. 4), and mean stress axes calculated from such data (technique of A. Michaels, submitted). Results are shown in Figure 6C, and stress axes parallel strain axes.

Magmatic Terrane

To a first approximation, the northern edge of the magmatic terrane can be best thought of as a 2-4 km wide highly strained zone that strikes N70W, parallel to the Florence-Niagara Fault (Fig. 5B). In detail, the penetrative vertical foliation that defines the shear zone fabric has been refolded about subvertical axes during a subsequent deformation event.

In this region a dominant structural feature is the Dunbar Gneiss dome, which Sims (pers. comm., 1982) invokes to account for variable foliation attitudes at the edges of the gneiss body. Relative timing of gneiss doming and later folding of the penetrative foliation near the fault is unresolved.

Structural Synthesis of the Magmatic Terrane. The earliest recognizable deformation, D1, produced a penetrative, subvertical, regionally WNW-striking foliation S1 with a steep down-dip mineral lineation L1. Boudinage and dismembered isoclinal folds indicate great strain accompanied D1. Early metamorphism M1 was synkinematic with D1 and probably attained amphibolite facies P-T conditions. Subsequent open to tight folding comprised D2; these folds range from cm to km in wavelength, have subvertical axes, and do not signify a penetrative deformation event. Retrograde thermal metamorphism, M2, generated randomly oriented amphibole and chlorite that overprint the M1 metamorphic fabric. It is not known whether M2 is post- or syn-D2.

Several structural features indicate that D1 was accompanied by great strain. Isoclinally folded compositional layering and, in some metasedimentary rocks, bedding, is almost always tectonically dismembered. The resultant boudins have their long axes or major planes oriented parallel to the penetrative S1 foliation. Pressure shadows around some mineral grains lend support to an interpretation of L1 as a stretching lineation. Finally, when D2 folding is removed, D1 fold axes define a great circle distribution within a constant mean axial surface of approximately N70W (Fig. 6D). Removal of D2 folds also yields a point maximum of mineral (stretching) lineations plunging steeply southwest. From this geometry we infer axes of the strain ellipsoid during D1 to be X subvertical, Y subhorizontal WNW-ESE, and Z subhorizontal NNE-SSW. Hence X corresponds with L1, the XY plane corresponds with S1, and the shortening direction Z lies roughly normal to N70W and the Florence-Niagara Fault.

Further support for this orientation of the D1 strain axes was recently obtained from slickenside striations on minor faults in the mt. Using a computer program developed by Andrew Michael of Stanford University, we calculated axes of the

stress ellipsoid (σ_1 , σ_2 , σ_3) that coincide almost exactly with the strain axes, Z, Y, and X (Fig. 6E). The close agreement of axes orientations derived from two markedly different techniques, coupled with the tiny 95% confidence circles for the σ values, strongly indicate NNE-SSW shortening and subvertical extension during D1.

The earliest metamorphism, M1, was synkinematic with D1 as evidenced by alignment of relict amphibole grains within the S1 foliation plane and parallel to L1. In thin section, however, little or none of the original M1 mineral assemblage can be identified due to retrograde metamorphism during M2.

During D2, D1 layering was folded about subvertical axes both at outcrop scale, where close to open cm to meter wavelength folds are observed, and at map scale, where homogeneous domains having variable, but always steep, orientations of D1 foliation/layering are best explained as limbs of open folds with wavelengths measured in km. Axial surfaces of these folds are variable but usually imply E-W to NW-SE shortening. No penetrative S-surface or lineation accompanies D2.

The preponderance of randomly-oriented green amphibole and chlorite in rocks of all lithotypes suggests that the magmatic terrane experience late thermal metamorphic retrogression of M1 amphibolite facies assemblages to M2 greenschist facies assemblages. We have no direct evidence pertaining to whether M2 is post- or syn-D2.

Also present in the magmatic terrane are local areas in which crenulations are developed that appear to be parallel to crenulation cleavages in the miogeocline and FNT. However, we do not have enough data at present to conclude whether all deformation phases observed in the miogeocline are present in the mt, and whether the ordering of these events is similar.

HIGH STRAIN BELT: NATURE OF THE MT-FNT BOUNDARY.

The FNT and northern mt define a high strain belt, where fold axes have been locally strained into parallelism with the direction of finite extension (Fig. 5)(Larue and Ueng, submitted; Sedlock and Larue, 1983). Other features associated with this great strain are isoclinal folds, dismembered folds, type 2 and 3 folds (of Ramsay, 1967) and transposed layering. Large strains such as those inferred here occur only rarely in rocks north of the FNT. The southern boundary of the high strain belt has not been adequately defined. We conclude that the FNT and northern part of the mt represents a high strain belt straddling the Florence-Niagara Fault. The northern zone (FNT) is developed within the miogeoclinal assemblage rocks, whereas the southern zone affects only arc assemblage rocks (northern part of mt). Structural fabrics are nearly identical (Fig. 6B-E). This high strain belt probably formed during terrane accretion.

Other zones of high strain including shear zones occur locally throughout the miogeocline and probably represent zones of increased strain resulting from localized weaknesses in the basement.

GEOCHEMISTRY

Provenance of Marquette Range Supergroup

sandstones is not well constrained because diagenesis and metamorphism has altered and destroyed lithic fragments such that modified assemblages exist. Petrographic studies of only slightly metamorphosed sandstones indicates an older Precambrian source for the Chocoley, Menominee (Larue, 1981) and Baraga Groups (Alwin, 1979). However, a significant portion of the Marquette Range Supergroup is represented by slate, whose provenance is extremely difficult to establish petrographically.

To try to characterize the provenance of the slates, we sent about 60 samples from throughout the early Proterozoic section to the Barringer-Majenta Corporation, who made major and trace element studies using induced coupled plasma techniques (ICP). Several duplicate samples were sent and errors were in all cases <5%. Tom Vogel (Michigan State University, pers. comm., 1980) has had similar success with them.

Provenance studies using slate geochemistry have been made by Garrels and MacKenzie (1971), Cameron and Garrels (1981) and others, who used geochemistry to separate slates of volcanic and continental provenance. In our study, we made 106 ternary diagrams of which 4 are shown (Fig. 7) representing different combinations of major and minor elements of the slates, and also plotted average argillite, average granite and average greenstone from the Canadian shield (Ronov and Migdisov, 1971). In addition, analyses of the Badwater Greenstone are plotted in Figure 7.

Samples used in our study are mostly from the areas discussed herein, but we also included samples from the Marquette trough (especially the Sismo Slate of the Menominee Group which underlies the Negaunee Iron Formation).

Two basic populations are recognized in the ternary diagrams presented herein in which formational groupings occurred. Slates interbedded

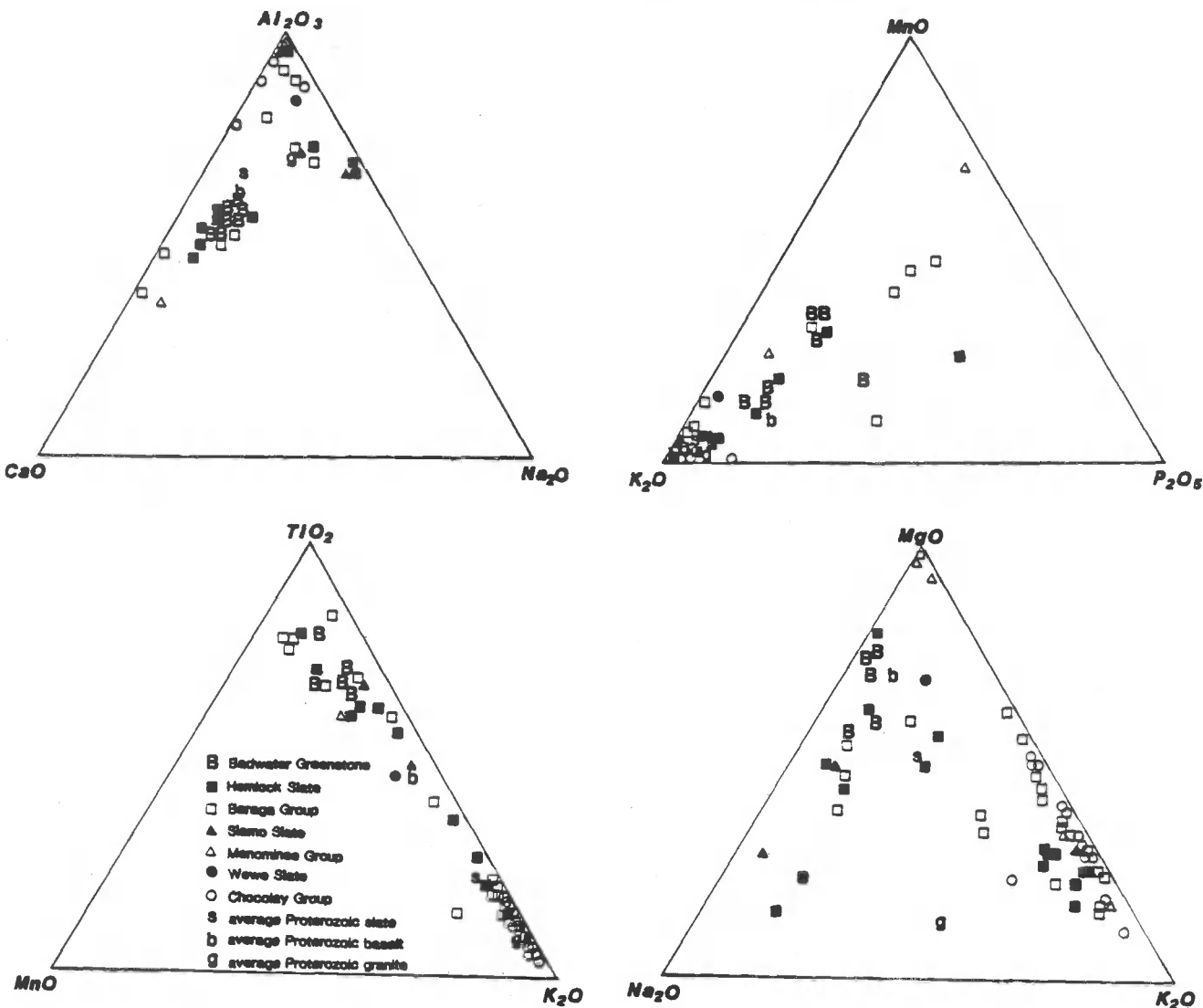


Fig. 7 Ternary plots of slate geochemistry.

with ultramature quartzites and dolomites of the Chocoday Group generally plot in a tight cluster near composition of the average granite. Such potassic and aluminous slates were probably originally illitic, and derived from a continental source. Slates from the Menominee and Baraga (including Hemlock Slates) seem to represent mixed source-continental plus volcanic. Some slates from the Siamo Slate have bulk geochemistry similar to greenstones, probably indicating a volcanogenic source. Although volcanic rocks have been recognized in the upper part of the Menominee Group (Prinz, 1976), this is the first indication that pre-iron formation strata, specifically the Siamo Slate contain volcanogenic material. Gair and Thaden (1968) proposed, also on the basis of geochemistry, that certain of the Weve Slates (uppermost unit of the Chocoday Group in the Marquette trough) were volcanogenic. A single data point from Gair and Thaden is plotted in Figure 7.

In conclusion, it appears that volcanism occurred sporadically throughout Marquette Range Supergroup sedimentation. It appears that Chocoday Group sediments were derived exclusively from a continental (older Precambrian) source, with a minor influx of volcanogenic sedimentation occurring late in its depositional history. Unconformably overlying Menominee Group quartzites also represent purely continental provenance, but Siamo Slate turbidites contain significant amounts (as yet not ascertained) of volcanogenic slates. Volcanics are also interstratified with Menominee Group iron formation in the Gogebic Range (Prinz, 1976). Baraga Group slates also contain both continentally-derived, mixed, and volcanogenically-derived slates. Thus, volcanism seems to have been significant and long-lived from Menominee Group through Baraga Group sedimentation. Volcanic rocks of this age are known to represent continental tholeiites based on other studies (Fox, 1982; Cudzillo, 1978).

SUMMARY

This study establishes that the Proterozoic rocks in the south central Lake Superior region have suffered a complicated, polyphase deformation history. The exact tectonic interpretation of each deformation event is not yet fully understood. However, it is clear that the CFT, FNT, mt, and miogeocline have undergone parallel deformation histories. By removing all deformations except F1, some interesting tectonolithological assemblages are observed: the non-volcanic miogeocline (subterrane A), submarine tholeiitic volcanics of subterrane B; basin floor deposits (Crystal Falls terrane), highly strained fault packets (FNT), and the magmatic terrane, from NE to SW in sequence. These assemblages were juxtaposed together by the end of deformation F1. Later deformations were responsible for rotation of the regional structural features (Fig. 8).

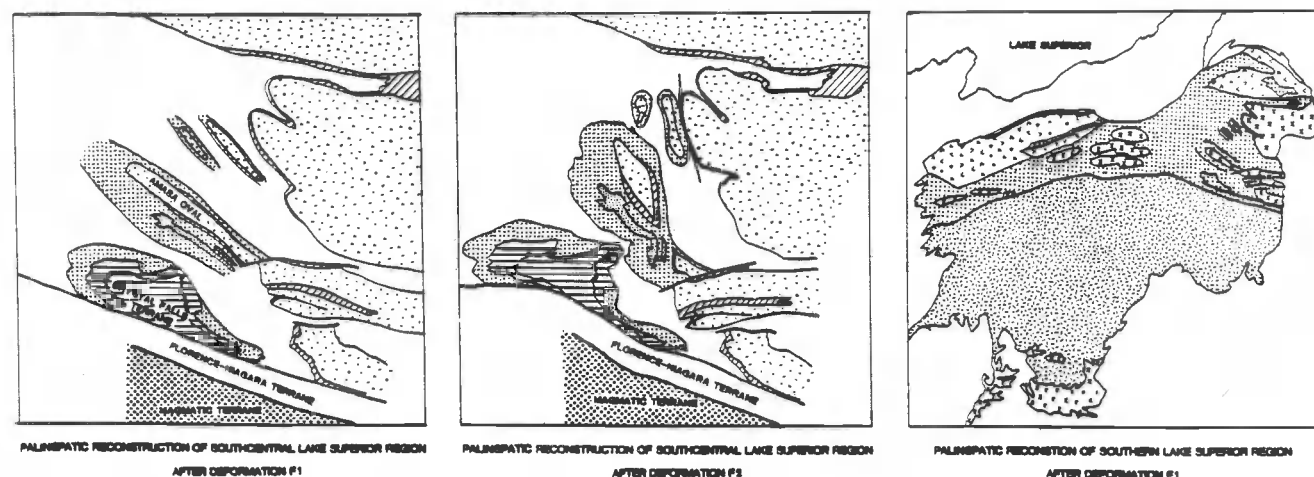


Fig. 8 Palinspastic restoration of the southern Lake Superior region. Compare with Figure 1.

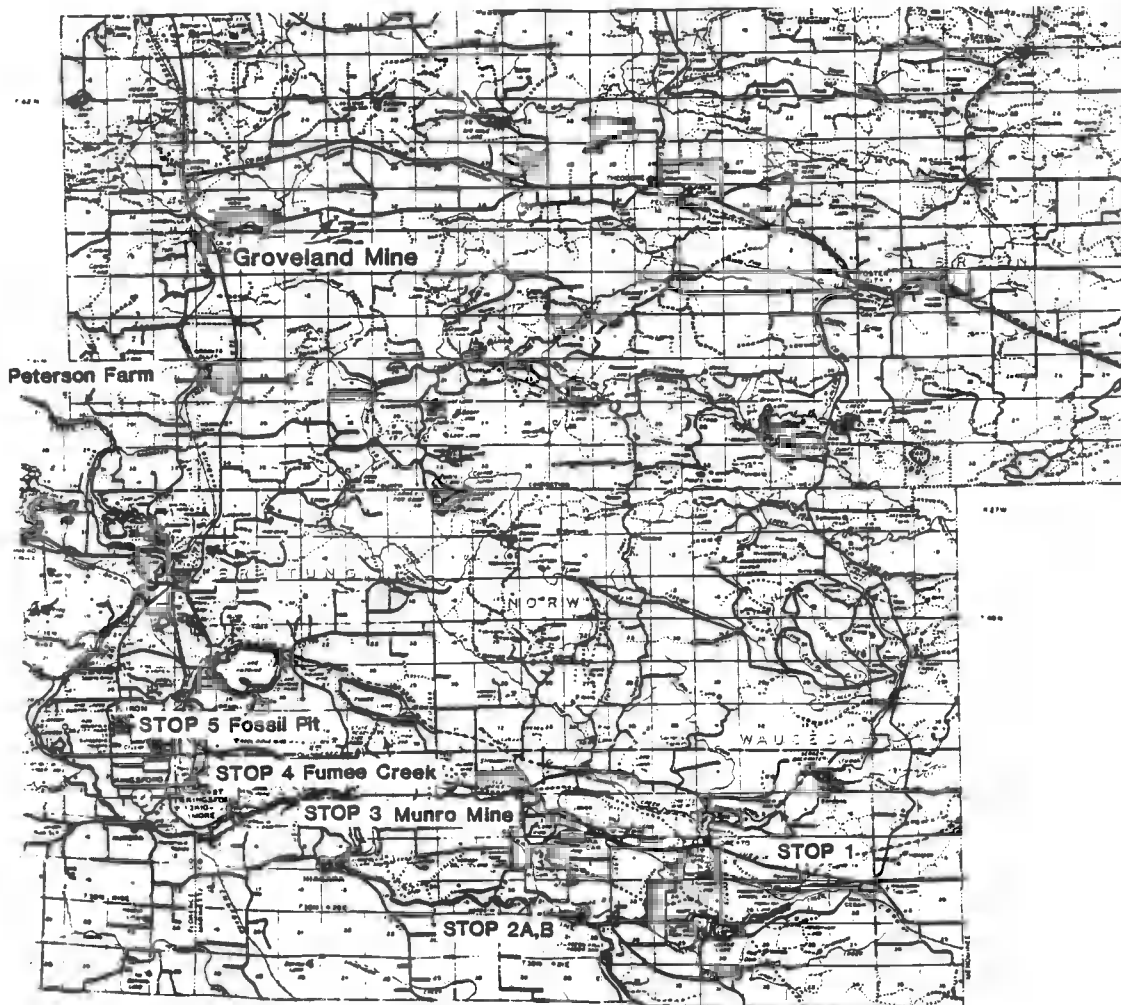
Field Trip Road Log

Stop 1 Sturgeon Falls dam. Park at end of road. Obtain permission to look at rocks from dam keeper. Excellent exposures of Archean granitoid basement. Fern Creek Formation, and, down the road a piece, Sturgeon Quartzite. Fern Creek and Sturgeon Quartzite represent basal units of the Chocoday Group.

This outcrop is famous because Pettijohn (1943) and Trow (1948) claimed that the Fern Creek represents glacial sedimentation. More recently, Larue (1981a) suggested an alluvial origin was more appropriate. Because the rocks at the damsite are extremely deformed, compelling data will probably never be presented. Last summer, one of us (D. Kasper) spent one week studying the Fern Creek section, and concluded that the sequence was as a whole fining-upward (see Figure RL-2), but that several smaller fining-upward and coarsening-upward cycles are apparent. We conclude that the basal sections represents channelized deposits (fining-upward sequences), whereas the upper sandier sections represent progradation of sheet-like sand bodies (coarsening upward sequences). Such an overall package of channelized bodies overlain by sheet-sand bodies, capped by

Mileage

- 0.0 Leave Dickinson Inn, Iron Mountain, Michigan (Fig. RL-1)
- 0.1 Right turn onto Stephenson (U.S. 2). (Go south).
- 4.2 Town of Quinnesec
- 4.6 Fumee Creek. Excellent continuous exposures of Randville Dolomite. Good algal structures. (This will be Stop 4).
- 8.4 Town of Norway.
- 13.1 Flashing light (State Street). Turn left. (North). Town of Loretto.
- 13.7 Right on paved road.
- 14.8 Left on gravel road.



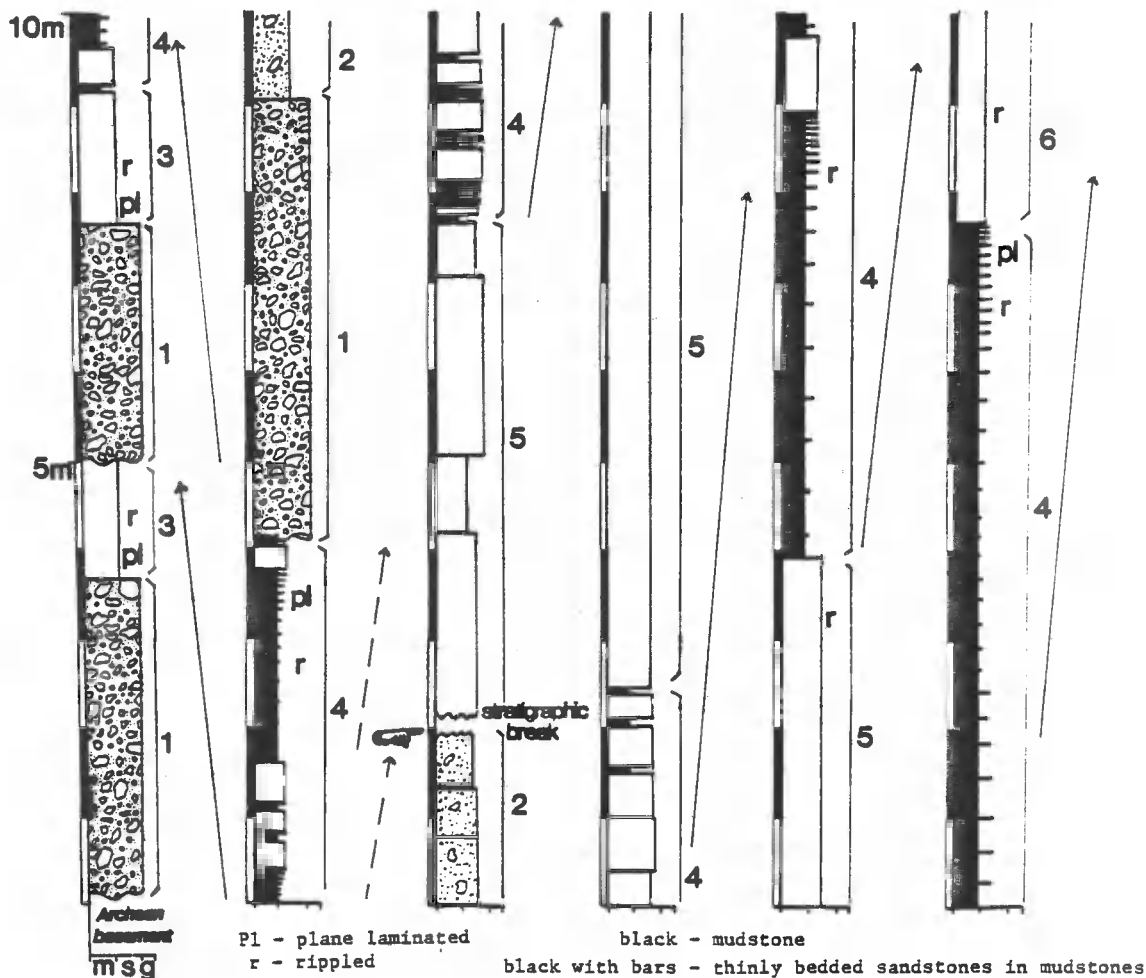
RL-1 Location map of Stops 1-5. (Map courtesy of tourist bureau)

nearshore sands of the Sturgeon Quartzite seems best interpreted as the flooding of a fan delta. That is, a fan delta with more proximal channelized gravels and distal sheet sands, feeding a nearshore environment, was drowned by a rise in sea level.

Although we prefer the fan delta argument,

perhaps a glacial fan delta is also allowable.

The Sturgeon Quartzite is also an interesting unit, because of its great thickness (~ 700 m) and extremely unidirectional paleocurrents (directed SE). The sedimentology of the Sturgeon Quartzite is discussed in Larue (1980).



RL-2 Stratigraphic section at Fern Creek dam (Stop 1). Fern Creek Formation topping in Sturgeon Quartzite. Numbers here are facies described in appendix.

- 15.5 Leave Sturgeon Falls dam. Go back toward Loretto.
- 16.5 Right on main road.
- 17.3 Left on road (back to Loretto).
- 17.9 Right on U.S. 2 at Loretto.
- 22.4 Left on Section Street (town of Norway).
- 23.4 Section becomes Forest Street.
- 23.5 Left on Pine Drive.
- 23.7 Stop 2A Slates near Hanbury Lake. As shown in Figure 4 of the text, Larue and

Ueng (submitted) separate the fault-bound Florence-Niagara terrane (FNT) from the other rocks of the Marquette Range Supergroup and underlying Archean basement, based on differences in structure and lithology observed in the FNT. The separation of the FNT from the rest of the Lake Superior miogeocline was based in large part on studies made at Hanbury Lake. Strata exposed at Hanbury Lake are thought to represent the Michigamme Formation of the Baraga Group. However, unlike other Michigamme Formation strata, rocks at Hanbury Lake include quartzites (probably turbidites) and dolomites (deep-water?). Deep-water

quartzites and dolomites are not present elsewhere in the Lake Superior region in the Michigamme Formation to our knowledge. Therefore, the lithology of strata exposed at Hanbury Lake is not directly comparable to Michigamme Formation strata in the miogeoclinal realm of the Lake Superior region (north of the FNT).

Secondly, the rocks at Hanbury Lake have experienced great strain. Fold axes have been stretched into local parallelism with the direction of bulk extension. This is not observed elsewhere in the Lake Superior region except perhaps near the Republic Mine.

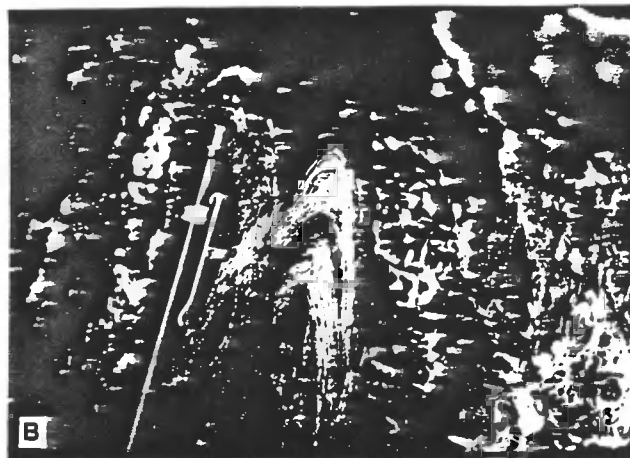
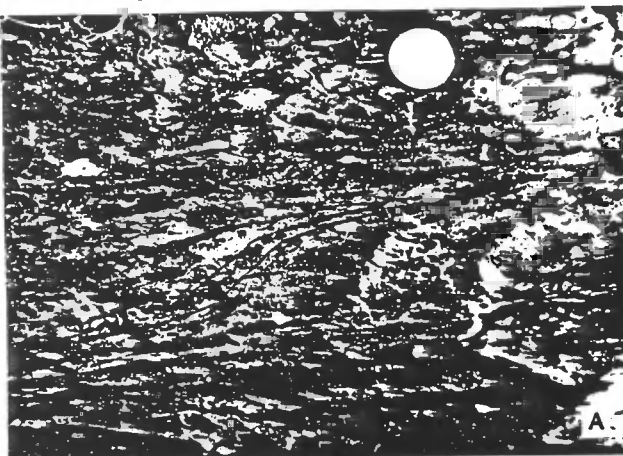
At Stop 2A, low outcrops by the road show examples of slate near Hanbury Lake. Foliation strikes WNW, and dips steeply south. A wrinkle lineation plunges down the foliation, parallel to

a stretching direction observed elsewhere. Bedding is locally transposed into the foliation (Fig. RL-3A). Quartz veins are boudinaged and folded locally.

24.0

Stop 2B. Park near bend in road. Ask permission to trespass from nice people in house before curve. Hike up hill behind house to crest, down to small pasture, up to next low hill where spectacular folds are exposed.

Folds (Fig. RL-3B) have axes sub-parallel to direction of extension, have attenuated limbs, are tight to isoclinal, and have probably undergone great finite strain. Larue and Ueng (in preparation) suggest X/Z ratios of around 10 are required to account for the observed fabric and structures.



RL-3 Fold of Michigamme Formation, Stop 2.

25.7. Turn around and backtrack to U.S. 2. Left on U.S. 2 (go west).

27.6 Right turn on dirt road after "Begin Only" sign.

Stop 3. Munro mine. Bayley and others (1966) consider that the Monroe mine exposes only Trader's Iron-bearing member of the Vulcan Iron Formation. These rocks are thin bedded, siliceous, and are tightly folded locally. The regional structure of the pit is a south-dipping homocline complicated by minor folds. Fold axes plunge subhorizontally, and axial planes dip steeply. Some box folds are present and have one subhorizontal axial plane. Slickenside striations on bedding surfaces are distributed in a plane perpendicular to the fold axis.

Hans Hofmann, the Canadian stromatolite expert, told us (1981) that trace fossils had been described at this locality, but together we found none. The principal point of this outcrop is the marked change in fold axis

orientation from the previous outcrop. At Stop 2, fold axes are girdled in a constant mean axial plane. At Stop 3, fold axes are all subhorizontal in the same mean axial plane. Larue and Ueng (submitted) suggest that there is a structural discontinuity that separates the highly strained rocks of outcrop 2 with the less strained rocks observed in the Munro mine.

Go back to U.S. 2 and proceed NW (turn right).

29.7

Fumee Creek. Stop 4. Exposed at Fumee Creek is an excellent homoclinal south-dipping section of Randville dolomite, in fault contact with Michigamme Formation (Bayley and others, 1966). This upper part of the Randville contains almost no clastic detritus. Minor folds with axes subparallel to those observed at Stop 3 are present locally in cherty beds. Algal structures are exposed (Fig. RL-4) on the railroad grade perpendicular to the creek.



RL-4 Cryptalgal structures, Stop 4

Go back to car. Proceed NW on U.S. 2.

30.2 Turn right at town of Quinnesec.

33.1 Turn left at Lake Antoine Rd.

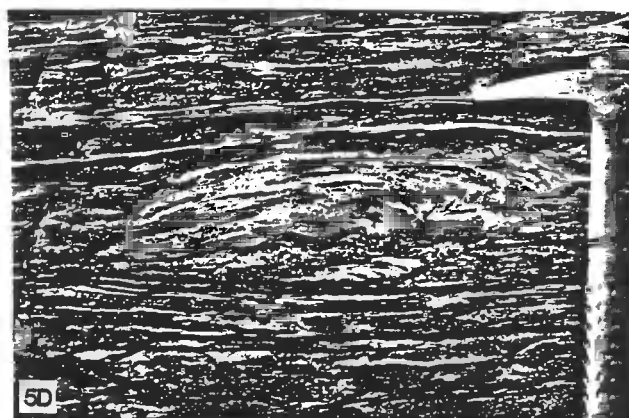
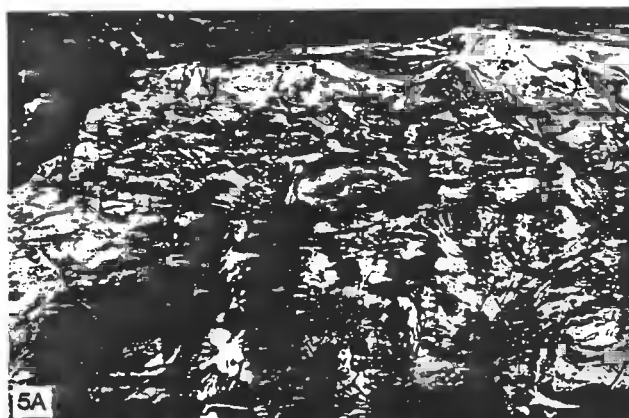
34.3 Stop at Randville Quarry. Stop 5. You could spend months studying this outcrop. Strained and folded algal structures, strained mudcracks, minor folds, intraclastic dolomite, mud-draped ripples (Fig. RL-5). Note the abundance of coarse-grained sand in this lower part of the Randville. The sand is feldspathic and derived from a granitic source. Excellent exposures of Randville Dolomite are also found on the island 150 m to the WNW.

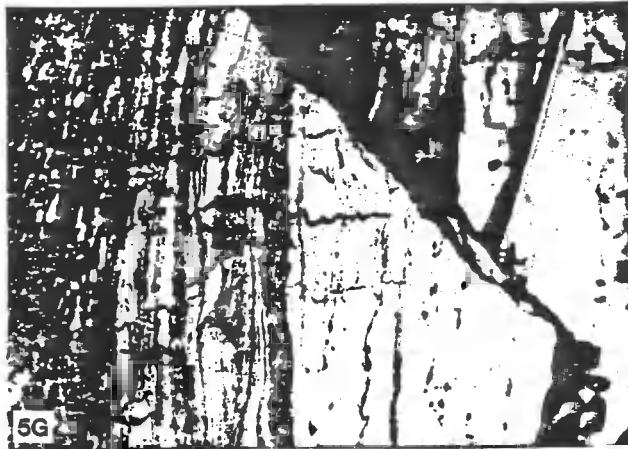
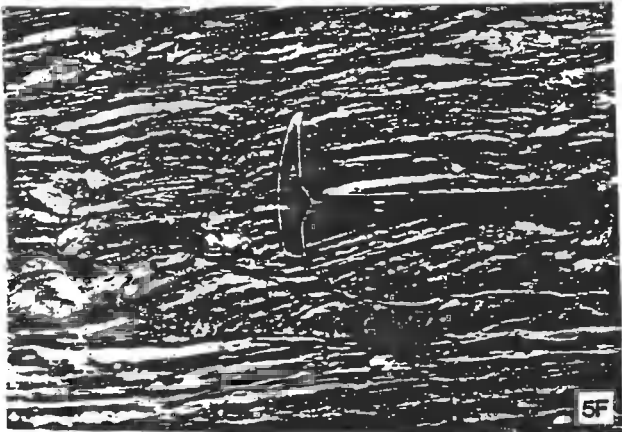
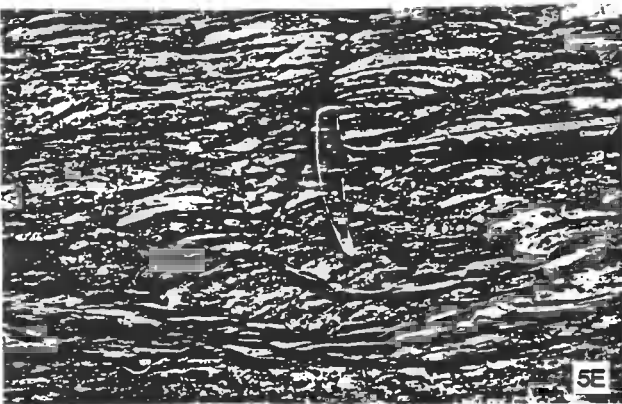
Structurally, the most interesting problem here is that the algal structures have been stretched parallel to local fold axes (trending W, plunging 15-40°)(Fig. RL-5A). Most stretching lineations in the Florence-Niagara terrane plunges about 70-90°W. Fold axis parallel stretching lineations can occur when a compacted rock is then strained.

Another interesting structure is one we call "tornado" structures (Fig. RL-5E,F). These are deformed algal stromatolites that have been folded such that they look, in cross-section, like a tornado touching down. Other deformation features of the stromatolites include folding of individual laminae.

These stromatolites obviously represent intertidal structures because they are interstratified with mud-cracked strata.

Another interesting point to reflect on is the monstrous thickness (700 m) of the Randville Dolomite in the Fnt. Was this really deposited on Sturgeon Quartzite?



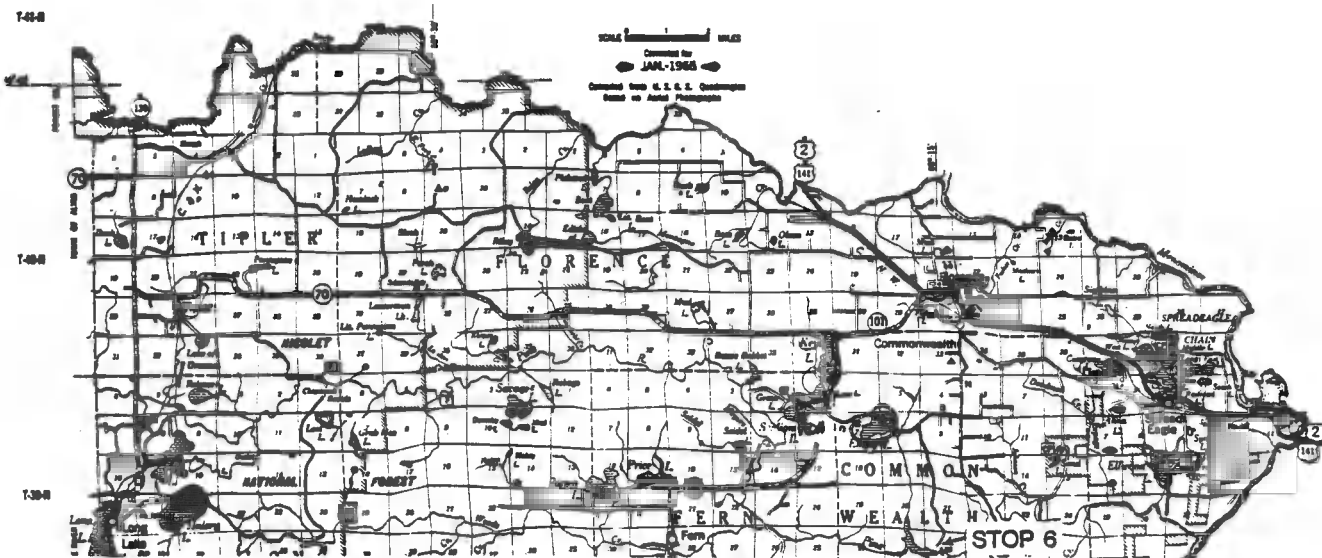


RL-5 A. Plan view of strained cryptalgal stromatolite domes. Lineation plunges about 30° W. Randville Dolomite, Stop 5. B,C. Cross-sections of strained cryptalgal structures, Stop 5. D. Folded cryptalgal lamination. E,F. Tornado structures (folded algal columns). G. Molar teeth in Randville Dolomite, Stop 5. Origin unknown.

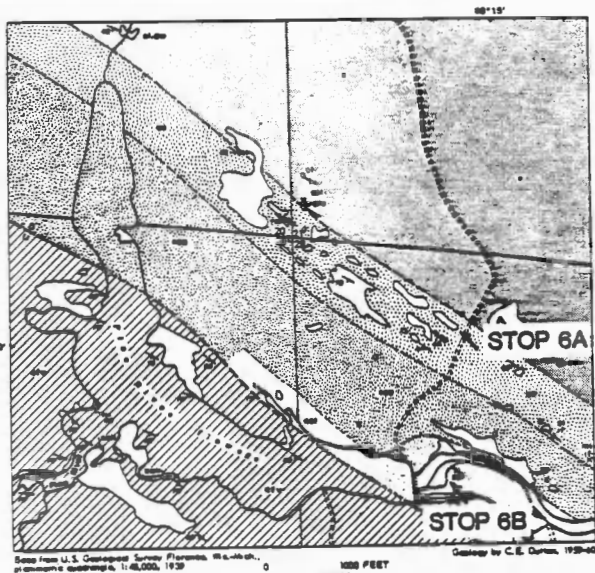
Proceed on Lake Antoine Rd. which becomes Margaret Street.

35.7 Turn right at U.S. 2. From here on the field guide gets sketchy in that the individual miles aren't counted. However, there is only one more stop left in this field trip. (Fig. RL-6 is a map).

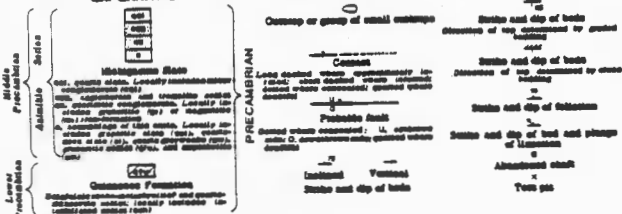
Drive NW on U.S. 2 for approximately 15 miles until you reach the town of Florence, Wisconsin. In the center of town, take County Road N south (turn left from U.S. 2). Drive for about 3 miles on N until it intersects County Road D. Turn right at D and proceed for about 1 mile until you see the road to the Pine River Dam public



RL-6 Map showing Florence and vicinity, Wisconsin and Stop 6. (Map courtesy of local tourist bureau)



EXPLANATION



RL-7 Blow-up of Fig. RL-6 with geology, from Dutton, 1971.

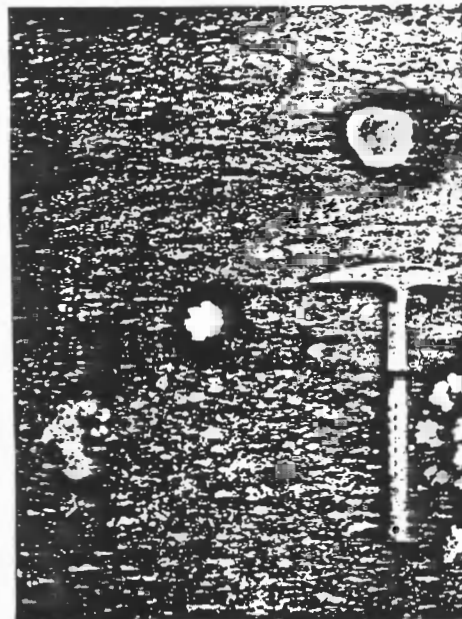
access (see Fig. RL-6). Take this road (it only goes south) to the end and park near the water (see Fig. RL-7).

Walk back up the road $\frac{1}{2}$ mile until you reach the hill crest, outcrops are off to the west 150 m.

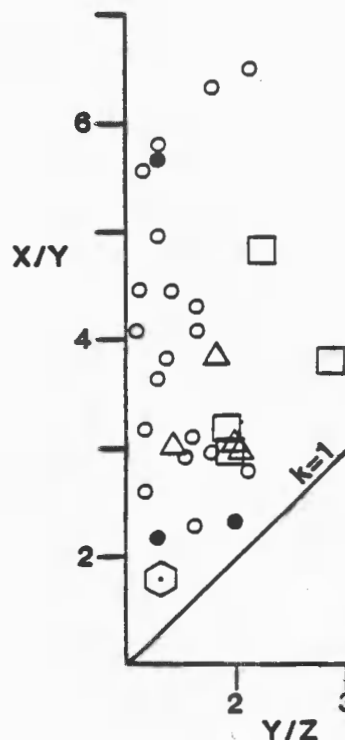
Stop 6a Stop 6a is an exposure of pebbly quartzitic sandstones (Fig. RL-8) in the Michigamme Formation of the Florence-Niagara terrane. The rocks are exposed in a south-facing homocline, about half a kilometer in maximum thickness. Strata are composed of pebble beds, sandstone beds and pebbly sandstone beds are commonly plane-laminated or cross-laminated. Sediments are extremely quartzose, rare argillite pebbles are present. Deposition occurred in shallow water (Nilsen, 1965), possibly by fluvial processes.

Pebbles in the quartzite have been stretched into cigar-shaped (constrictional strain) (Fig. RL-9). Such extreme strains make paleocurrent studies (Nilsen, 1965) doubtful.

Go back to the dam and walk down to the rocks exposed below the dam.



RL-8 Pebbly sandstones in "Michigamme Formation" at Stop 6A. Layering sketched in at left.



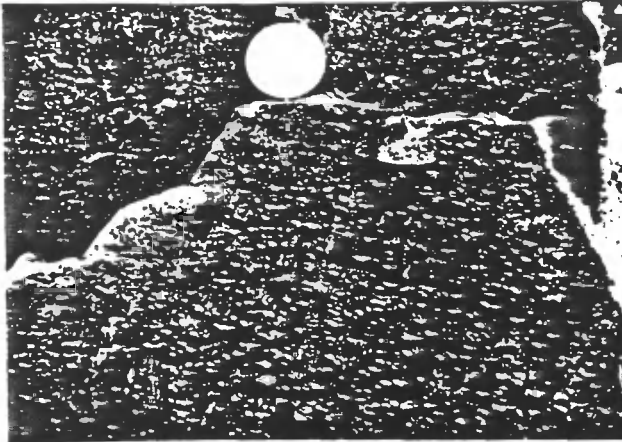
RL-9 Strain data (Rf/ϕ technique) from Stop 6A (hollow circles, squares, triangles) and northern quartzite (packet 7 of squares, triangles) and northern quartzite (packet 7 of Fig. 4; filled circles) and Lake Antoine area (Stop 5) (hexagon).

Stop 6b. Exposed along the spillway of the dam is a spectacular homoclinal (? top indicators are rare) section of slate with local sandstone interbeds. In the hills just north of the spillway are highly deformed volcanic rocks (agglomerates of Dutton, 1970).

Interesting features at the damsite are foliations with strongly developed down dip lineation.

This lineation can be shown to be of two origins: a stretching lineation and an intersection (foliation x foliation) intersection.

Zoned garnets are locally present and define a shallowly-plunging lineation in the dominant NW-trending foliation (Fig. RL-10).



RL-10 Oriented garnets (plunging SE), cross-cutting down-dip lineation. Quarter for scale. Michigamme Formation, Stop 6B.

Folds with steeply plunging axes disrupt the regional homocline and can be shown to be associated with strike-slip fault zones.

The structural history of the outcrop is discussed in Larue and Ueng (in preparation). The dominant NW trending homocline with bedding-parallel foliation is a product of the earliest deformation. Metamorphism during this deformation was probably low grade. The second foliation, which cross-cuts the first at high angles, occurred next, and was associated with biotite-grade metamorphism. Strike-slip faulting was concurrent with development of folds with steep axes occurred last and was also associated with garnet grade metamorphism. Garnets grew with long axes parallel to the extension direction (subhorizontal).

Summary of Stop 6. What should strike even the most casual observer about Stop 6 is the contiguity of shallow water quartzites with deep-water

slates and volcanics. This great change in stratigraphy is not accompanied by any gradational changes, and therefore we conclude that Stop 6a and 6b are separated by a major fault.

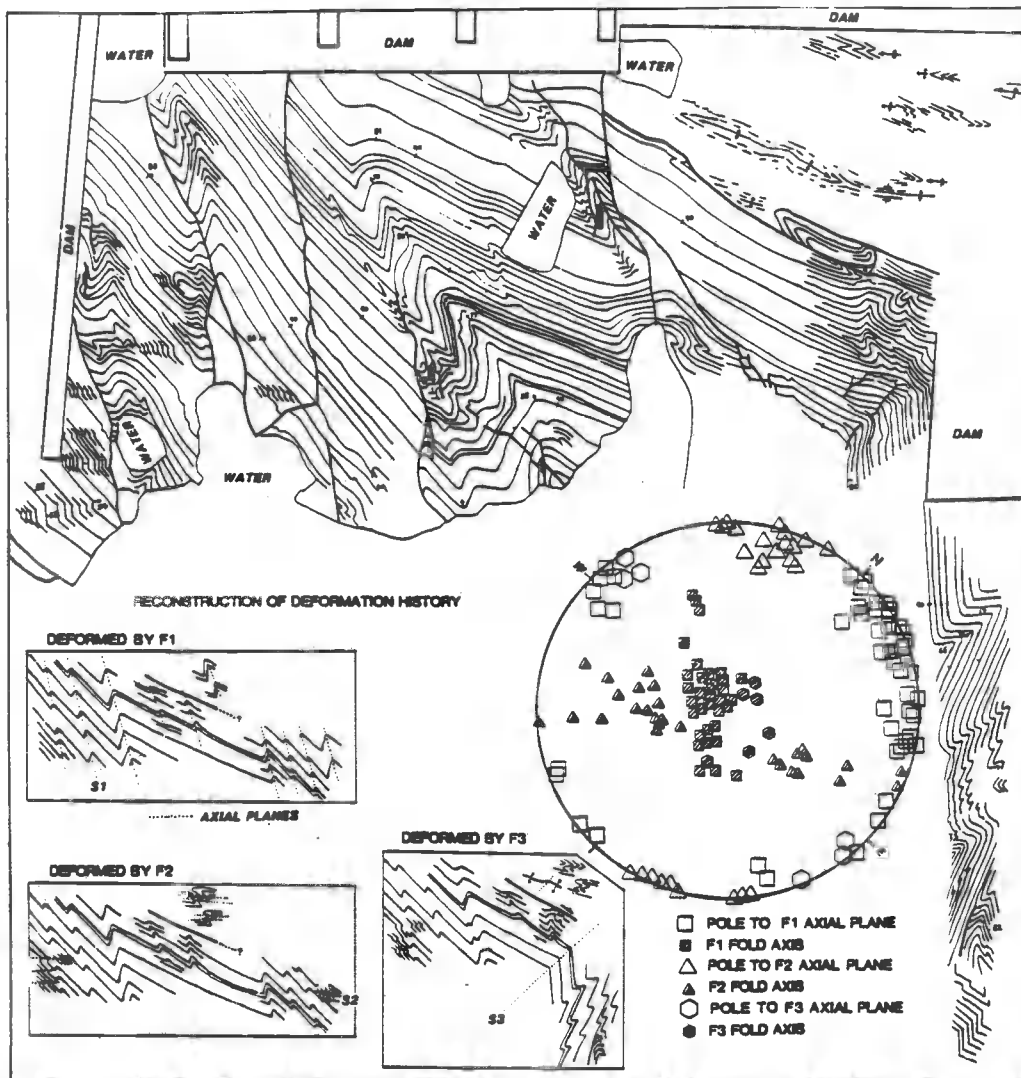
In summarizing the FNT, the occurrence of shallow water quartzites in two locations (at Stop 6a and also to the NW; see Fig. 4) in contact with deep-water locally volcanogenic shales suggests that both quartzite units are fault bound. Further, the changes in structural style between slaty rocks and those of the Chocoma and Menominee Groups suggests a fault separation as well. Finally, if one adds these faults to those previously described by Bayley and others (1966) and Dutton (1970), one reaches the conclusion that the FNT is a collage of fault bound slices.

Optional Field Stop - Paint River Dam

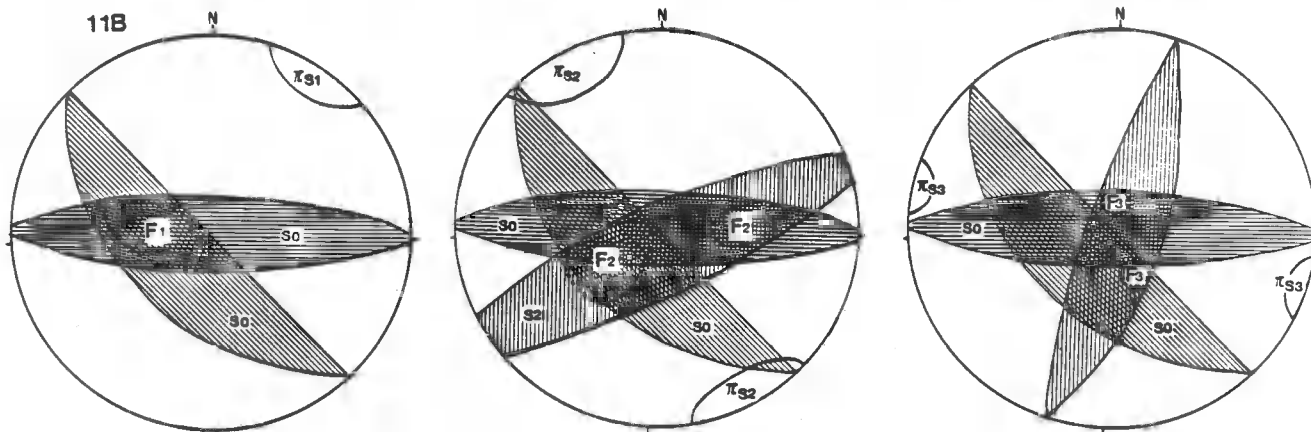
Location: Return to Florence, Wisconsin, and proceed NW on U.S. 2 to Crystal Falls, Michigan. When you reach the blinking red light in Crystal Falls (intersection with M-69), proceed on U.S. 2 past the Red Owl (one block, on right), and into the left curve of U.S. 2 (about 2 blocks from blinking red light). Turn right on the street next to the abandoned gas station and proceed down hill, cross the Paint River (about 1 mile) and park in dirt lot on left. Walk over to dam spillway.

Geology: The Riverton iron formation exposed at this damsite was deformed by three phases of deformation, the F1, F2, and F3 events discussed in the text, to form a complicated mosaic of folds. Axial planes of F1 folds commonly strike WNW and dip vertically, except those F1 folds cropping out on the NE bank of the river (Figure RL-11). Axial planes of F1 folds exposed on the NE bank were rotated by a later folding event of F3 to a NS orientation. Apical angles of F1 folds generally show type 1b, 1c and type 3 folds of Ramsay's classification scheme (1967). The beds were folded by F1 to form two sets of homoclinal limbs with strikes of N50W and EW. Because the orientations of these homoclinal limbs with respect to the flattening planes of later deformations are not the same, the fold styles of later deformations imprinted on these two limbs are also distinctively different. In the southwest part of the outcrop, the F2 deformation folded the EW striking F1 limb into a series of open folds with fold axes plunging 50 degrees NE, in a NE-striking axial plane. Apical angles of these folds range from 100 to 120 degrees and fold profiles indicate type 1b and 1c folds. These open folds are the result of the small angle between the EW trending F1 limb and N65E striking flattening planes of F2 deformation. At the northern end of this outcrop the F2 deformation formed a

11A



11B



F1 folding created two homoclines (S0)

These homoclines were refolded by F2

S0 were refolded again by F3

RL-11A,B Structure of the Paint River damsite. See Roadlog.

series of much tighter folds, with fold axes plunging SW, by deforming the N50W oriented F1 fold limb. Apical angles of these folds are commonly smaller than 80 degrees and fold profiles indicate type 1b, 1c and type 3 folds. These tight folds partially reflect the parallelism of the original N50W striking F1 fold limb with the shortening direction of the F2 deformation regime.

Because the F2 deformation represents folding of a previously folded surface, F2 fold axes plunge at various angles and define a great circle distribution on the stereogram (Fig. RL-11B).

The F3, F4 deformations, which are present in other outcrops (see text) are not recorded in this outcrop. The F5 deformation bends the eastern part of this outcrop into parallelism with the river. Apical angles of F5 folds are commonly 120 degrees and fold profiles show type 1b, 1c folds.

On the NE bank of the river, most of the N-S trending folds with apical angles smaller than 80 degrees are F1 folds rotated by F5 (Fig. 11). However, there are a few F5 folds exposed at NE bank judging from the characteristic 120 degree apical angle.

Groveland Mine sec 31 R29W T42N

Location: The Groveland mine is a recently abandoned iron mine in the Felch trough (see Fig. RL-1 or James and others, 1966 for location). Take M95 north about 12 miles from Iron Mountain, turn east (right) on County Road 569, and follow signs to the Groveland mine. You must have permission to get into the pit!

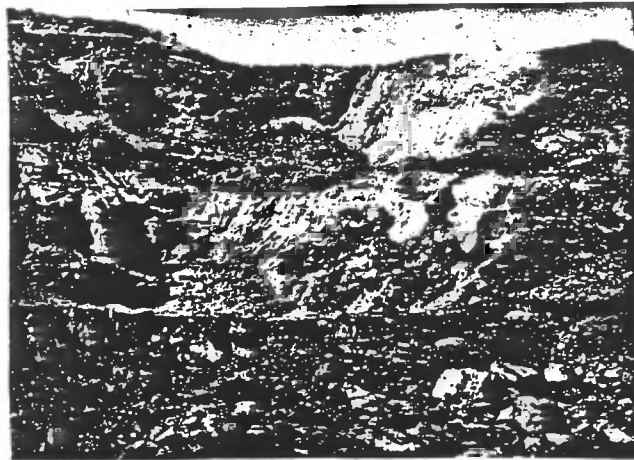
Geology: Most spectacular in this pit is the Chocoy Group Randville Dolomite in fault contact over Menominee Group Iron Formation; this fault is isoclinal folded. Therefore, this fault may represent a folded thrust fault. Unfolding the fault reveals a minimum heave of several hundred meters (Fig. RL-12).

The mine also contains numerous examples of folds, gorgeous foliations, kinks, metamorphic minerals and on and on.

East of town of Alpha SE $\frac{1}{4}$ sec 7 T42N R32W

Location: Start from town of Crystal Falls, the intersection of Highway 69 and Highway 2. Drive south on Highway 2 for 2.8 miles. Take right on the intersection to town of Alpha. Drive for 0.7 miles. Stop at a roadcut outcrop over a small hill.

Geology: The original N70W trending F1 folds in the Dunn Creek



RL-12 Randville Dolomite in fault contact over Vulcan Iron Formation, Groveland Mine, west face. Contact is isoclinally folded. Facing directions unknown.

slate were folded by F2 to a N15W trending orientation. Axial planes of these folds are still vertical. Fold styles of these folds are still similar to those F1 folds exposed at Paint River dam except with tighter apical angles. Fold profiles commonly show type 1b, 1c, and type 3 folds. At the eastern end of this outcrop, an EW oriented F2 fold was refolded by N-S oriented F5 deformation. Fold axes here are generally plunging north.

NW of Stager Lake NW $\frac{1}{4}$ sec 31 T42N R32W

Location: Start from town of Crystal Falls. Take Highway 2 south. Drive for roughly 9.5 miles. Take right turn on the intersection to Stager Lake. Drive for 2.4 miles northwest, passing Stager Lake. Take a dirt road to cross the railroad right before the paved road bends from NW to NNE. You will come to an open field. There is another railroad track about 200 yards away from you in the southwest. Pick up your backpack and hit this railroad track. Hike for $\frac{3}{4}$ mile toward NW on this track. This outcrop is present on both sides of the track.

Description: Deformed Dunn Creek slate here shows beautiful isoclinal folds and very tight folds. They are F1 folds which had been rotated by F2 deformation to a N-S trending orientation. Fold profiles commonly show 1b, 1c, and type 3 folds. Apical angles are commonly smaller than 30 degrees. Fold axes are generally gently dipping. Some dismembered isoclinal folds are present. The extreme flattening of these folds is probably accumulated from strain regimes of F1, F2, and F5.

NW of Peavy Pond NE1/4 sec 24 R32W T42N

Location: From town of Crystal Falls, drive 4.2 miles east on Highway 69. Turn to south at the intersection to Lake Mary. Drive 3.4 miles south passing Lake Mary. Turn right at the 3-way junction. Drive on this grit road toward the SW for 1 mile till you come to a fork. Take the road on right and slowly drive for another 0.35 miles. Stop exactly where the road begins to descend. Search for the outcrop in the woods to your right which is about 20 yards away from you.

Geology: Examine the pelitic portion of the outcrop. There are three sets of cleavages present in the rock, i.e. one set of slaty cleavage, two sets of crenulation cleavages. The S1 slaty cleavage strikes NE and is crenulated by S2 which strikes N65E. Both S1 and S2 cleavages dip vertically. However, S3 is a set of subhorizontal crenulation cleavage dipping NW and crosscutting both S1 and S2. The S3 crenulation cleavage here belongs to a group of subhorizontal crenulation cleavage dipping away from the Peavy Pond Intrusive, which is located SE of where you stand.

Neighborhood of Mansfield mine. sec 20 T43N R31W

Location: Go back to Highway 69. Drive east for 300 yards on Highway 69. Take left after spotting the sign of HEMLOCK DAM. Drive north for 2.8 miles till you come to a fork. Take the right road passing the one-lane bridge. Drive for another 0.2 miles till you hit the first series of road cut outcrops.

Geology: Some Hemlock pillows and slates are present here. The slates exposed at the south side of the road are a mixture of tuffaceous sediments and chert. The slates were baked by the neighboring Kiernan Sills to form abundant porphyroblasts. Under microscope, these porphyroblasts are nothing but pockets of chert doped with some tiny tourmaline crystals. However, porphyroblasts in outcrops half a mile south of here commonly show chistalite pseudomorphs. Climb up the northern hill of this outcrop. A cliff made of pillows is present at the western end of this hill. The depositional surface outlined by the pillows faces west and dips vertically. This N-S striking and vertically dipping depositional surface is paralleled by the bedding of slates and rhythmic layering in Kiernan Sills.

Among the over 2-mile thick Hemlock volcanics SW of the Amasa oval, pillows are ubiquitously present regardless of stratigraphic position.

Hemlock dam NE1/4 sec 18 R31W T43N

Location: Go back and pass the one-lane bridge. Take right turn heading north at the three way junction. Drive all the way to the end of the road. Ask for permission from a very nice person, Bob Graph, to enter the dam.

Geology: A series of fault bound packets of cherty sediments and pillows are exposed on the cliff at the northern end of dam. The rhythmic banding of sediments here are mixtures of tuffaceous sediments and chert. Graded bedding is not common. These sediments resemble ribbon cherts which represent deep sea sediments in orogenic belts. Some fallen blocks on the northern bank of the river, if you can cross the river, show depositional contacts among three major lithotypes, the massive lava flows and pillows, agglomerates, and ribbon cherts.

The deployment of the one-mile thick differentiated sills (Kiernan sills), pillow lavas, ferruginous sediments (iron formation), and ribbon chert in the neighborhood of Hemlock dam and Mansfield mine draws close resemblance to the upper part of ophiolite. It is true that the chemistry of Hemlock volcanics and Kiernan sills is not depleted enough to be characterized by MORB. However, the geological setting presented in front of you is a very rare case in the world where a layered intrusion was emplaced into a very thick pillow basalt sequence.

SW of Amasa NW1/4 sec 10 R32W T44N

Location: A map of Kelso Junction quadrangle (U.S.G.S. Bulletin 1226, plate 1) will be needed to get to this outcrop. Start from Paint River dam (optional outcrop 1) and drive north. It is about 11 miles of driving.

Geology: Some Hemlock slates and volcanics are exposed among several small mounds scattered within 100 yards here. Three phases of deformation are registered in these rocks, i.e. F1, F2, F3. F1 is shown by very tight folds and a penetrative slaty cleavage. The F1 slaty cleavage strikes N15W and is commonly present all through the rocks here. F2 crenulation cleavage is very subtle, but is commonly characterized by a set of vertical crenulation lineations showing on metavolcanics and carbonaceous slates. Stretched agglomerate pebbles plunge vertically in parallel with F1xF2 crenulation lineations. F3 is a set of subhorizontal crenulation cleavage that dips 25 degrees west and crosscuts F1. Some similar sets of subhorizontal cleavages dipping away from the Amasa oval have been observed.

The subhorizontal flattening plane shown by F3 cleavage here requires the uplift of the Amasa Oval basement to account for the vertical shortening. However, the uplift of Archean basement in Amasa oval has to occur later than the F1 and F2 deformation because F3 cleavage crosscuts both S1 and S2. Apparently, the magnitude of this uplift was minor such that the dips of the vertical S1 cleavage has not been rotated much.

Peterson's Farm SE1/4 sec 19 R30W T41N

Location: Start from town of Randville, drive south for 7.5 miles on county road 607. Turn right and drive 2.2 miles to the end of the road. Or when you leave Randville, drive south for 6.5 miles on State 95. Turn left and drive for 1.2 miles till you hit County 607. Make right turn heading north for 1/4 mile. Turn left and drive another 2.2 miles till you hit the end of the road. Get out of the car and ask permission from the owner. The outcrops are scattered about 150 yards N15E from you.

Description: The Michigamme slate exposed in these rocks registered at least 4 deformations, i.e. F1, F3, F4, F5. Almost all the pelitic portions of these rocks record 3 sets of cleavages at least. However, the best outcrop is an 8-foot tall, 15 feet wide block sitting atop a very gentle hill. Here the S1 slaty cleavage is crenulated by S3 crenulation cleavage. The crenulation of S3 fabric is so intense that it resembles bedding, but it is not. The S3 crenulation cleavages were folded into a NW trending fold by F4. F5 crenulation cleavage is imprinted on everything exposed here. To the middle toward west end of this outcrop, another set of subhorizontal cleavage is clearly present. This set of subhorizontal cleavage dips SE and may very well be related to the uplift of Peavy Pond intrusive.

APPENDIX

Facies descriptions of stratigraphic section at Fern Creek dam (Stop 1).

Facies 1: Disorganized matrix-supported conglomerate. Mean grain size: 10 cm. Sedimentary structures: massive (amalgamated?) beds, tectonically aligned clasts subparallel to cleavage. Facies thickness: 2-5 m. Lower contact: irregular. Upper contact: tabular, abrupt. Interpretation: debris flow deposits.

Facies 2: Pebbly muddy sandstone. Mean grain size: 0.5 mm. Sedimentary structures: massive (amalgamated?) beds. Facies thickness: 3 m. Lower contact: tabular. Upper contact: not exposed. Interpretation: debris flow deposits.

Facies 3: Ripple and plane-laminated fine grained sandstone. Mean grain size: 0.3 mm. Bed thickness: 1-20 cm, mean - 3 cm. SS:Sh = 1-3. Sedimentary structures: ripple and plane-laminations, convoluted bedding. Facies thickness: 1-2 m. Lower contact: tabular. Upper contact: tabular or scoured. Interpretation: Lower to transitional flow regime bedforms.

Facies 4: Interbedded sandstone and shale. Bed thickness 1-30 cm, mean - 10 cm. SS:Sh = <1-10. Sedimentary structures: mud-draped ripples, diffuse plane laminations, massive beds. Facies thickness: 2-9 m. Lower contact: tabular. Upper contact: tabular or scoured. Interpretation: Lower flow regime deposits interbedded with suspended load deposits.

Facies 5: Massive medium to coarse grained sandstone. Mean grain size: 0.7 mm. SS:Sh = 10. Sedimentary structures: rare mud-draped ripples, diffuse plane laminations, massive (amalgamated?) beds. Facies thickness: 11-12 m. Lower contact: tabular, abrupt. Upper contact: tabular, abrupt. Interpretation: Lower to transitional flow regime sheet-flow deposits.

Facies 6: Fine-grained sandstone. Mean grain size: 0.3 mm. Bed thickness: 1-15 cm, mean - 4 cm. SS:Sh = > 10. Sedimentary structures: ripples. Facies thickness: 4-6 m. Lower contact: tabular, abrupt. Upper contact: gradational into the Sturgeon Quartzite. Interpretation: Lower to transitional flow regime deposits.

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