Tectonic Imbrication and Foredeep Development in the Penokean Orogen, East-Central Minnesota—An Interpretation Based on Regional Geophysics and the Results of Test-Drilling

The Penokean Orogeny in Minnesota and Upper Michigan—A Comparison of Structural Geology

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Chapters C and D are issued as a single volume and are not available separately

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

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Chapter C

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By D.L. Southwick[1] *and* G.B. Morey[1]

Abstract

Regional aeromagnetic and gravity data, substantiated by data from follow-up shallow drilling, archived exploration drilling, and sparse bedrock outcrop, are the basis for a plate-tectonic reinterpretation of the segment of the Early Proterozoic Penokean orogen that lies in Minnesota, immediately west of the crosscutting Midcontinent rift system (Middle Proterozoic). This segment occupies a major northwest-facing salient in which structural trends curve from east-west near Lake Superior to north-south in central Minnesota. Within that broad arc the orogen consists of a southerly internal fold-and-thrust belt that contains tectonically shuffled sequences of sedimentary and volcanic rock in several terranes of contrasting stratigraphy, structural style, and metamorphic grade, together with an external turbidite basin (Animikie basin) that has the attributes of a migrating foredeep. The deformed supracrustal rocks in the medial part of the fold-and-thrust belt are characterized by mainly continental-margin petrogenesis and by low to moderate metamorphic grade. The southernmost terrane in the fold-and-thrust belt contains amphibolite-grade metamorphic rocks and migmatite from deep tectonic levels, as well as abundant syntectonic and post-tectonic intrusions.

The Penokean orogen developed along the south margin of the Archean Superior craton as the craton margin was subducted toward the southeast (present directions). Crustal loading by imbricated thrust sheets produced a frontal downflexure that migrated cratonward as convergence and subduction continued, and the thick section of turbidite that makes up the bulk of the Animikie Group (Early Proterozoic) accumulated therein. Iron-formations were deposited in three distinct tectono-stratigraphic settings as the Penokean orogen evolved through time.

INTRODUCTION

The Penokean orogen is an Early Proterozoic deformed belt that trends west-southwest along the south margin of the Archean Superior craton (Card and Ciesielski, 1986; Hoffman, 1988). It is truncated on the east by the Grenville orogen, and on the southwest by the Central Plains orogen (Sims and Peterman, 1986) at a poorly defined location in the subsurface of Nebraska. Sedimentation, volcanism, deformation, and plutonism occurred variably and episodically along the Penokean trend over a span of time that began perhaps as early as 2,491±5 Ma with extension in the Lake Huron area and ended as late as 1,770±10 Ma with the emplacement of post-tectonic plutons in southern and east-central Minnesota (Andrews and others, 1986; Horan and others, 1987). There is no evidence to suggest that any one segment of the orogen was affected by the entire 700-m.y. interval of activity; rather, it appears that tectonism may have started in the east and migrated west, as first suggested by Young (1983).

The Minnesota segment of the Penokean orogen (fig. 1) is very poorly exposed, and its investigation therefore has relied heavily on geophysical techniques and drilling. The northwestern, tectonically external part of the orogen consists of the Animikie basin and at least two remnant outliers to its west and southwest (first recognized in the present study) that are analogous to the

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Animikie in their tectonic setting and sedimentary fill (figs. 1 and 2). Although the Animikie basin is best known for the huge iron ore deposits that occur in the Biwabik Iron-formation of the Mesabi iron range (Morey, 1983 and references therein), sparse outcrop, drilling, and aeromagnetic signature indicate that most sedimentary rocks in the basin are dark-colored, turbiditic graywacke and argillite in formations that stratigraphically overlie the Biwabik (Morey and Ojakangas, 1970; Lucente and Morey, 1983). The sedimentary succession along the northwest margin of the Animikie basin (the Early Proterozoic Animikie Group) rests with erosional unconformity on Archean basement. It consists of a basal quartz arenite–siltite unit that was deposited under tidal influence (Ojakangas, 1983), the overlying Biwabik Iron-formation deposited on a shallow marine shelf (Morey, 1983), and the very thick sequence of orogenic turbidite above the iron-formation. Folding and cleavage are lacking along the Mesabi iron range; broad, open folds with incipient slaty cleavage appear about 15 km south of the range (fig. 2) and folding becomes progressively tighter south of there (Southwick, 1987; Holst, 1982, 1984).

The southeastern, tectonically complex part of the Penokean orogen in Minnesota contains highly deformed sedimentary and volcanic rocks that have been metamorphosed under varying conditions. Overall, the intensity of deformation and metamorphism increases regionally from northwest to southeast. Prominent among the supracrustal rocks in the central part of the deformed belt are carbonaceous black slate, iron-formation, quartzite, and various mafic to intermediate volcanic rocks (now mainly of greenschist rank) that collectively constitute the Early Proterozoic Mille Lacs Group (Morey, 1978). The southern part of the belt contains supracrustal rocks of amphibolite and lower granulite grade, various kinds of gneiss (including some of documented Archean age; see Goldich and Fischer (1986) and Southwick and others (1988) for data and discussion), and an assortment of syntectonic to post-tectonic intrusions that range in age from about 1,980 to 1,770 Ma (Horan and others, 1987; Goldich and Fischer, 1986; Spencer and Hanson, 1984; Morey, 1978).

ACKNOWLEDGMENTS

This truly has been a group effort. We are especially grateful to Val W. Chandler, R.J. Ferderer, and K.E. Carlson for their assistance with geophysical interpretation, to P.L. McSwiggen for his insights into some of the complexities of east-central Minnesota, and to P.K. Sims and Cedric Iverson for sharing their accumulated wisdom on matters Penokean. We also thank Warren Beck for permission to quote isotopic data from his still-warm Ph. D. dissertation. Technical reviews by P.K. Sims and T.B. Holst and an informal critique by Paul Hoffman helped us codify our arguments, and are much appreciated.

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PREVIOUS INVESTIGATIONS

Various workers have attempted to correlate the weakly metamorphosed supracrustal rocks in the strongly deformed central zone of the orogen with those in the less deformed Animikie basin to the north (fig. 3), using units of iron-formation present in both terranes as the key correlative intervals. A fundamental and persistent question has been whether there are several units of Early Proterozoic iron-formation in central Minnesota or only one. The major iron-formation of the Cuyuna iron-mining district in the deformed zone of the orogen, the Trommald Formation of Schmidt (1963), was thought to be continuous with the Biwabik Iron-formation of the Animikie basin by Grout and Wolff (1955), Marsden (1972), and Morey (1978), whereas Zapffe (1925, 1933) had argued earlier that the two were separated by a regional unconformity and thus were not the same stratigraphic entities. The virtual lack of outcrop in the broad area between the Cuyuna and Mesabi mining districts (fig. 2) has contributed greatly to the uncertainty of these stratigraphic reconstructions. Nevertheless, this question has major tectonic implications because, if the iron-formations of the southern, more deformed internal and the northern, less deformed external terranes are physically parts of the same stratigraphic entity, then the terranes must have been contiguous at the time the iron-formation was deposited. If, on the other hand, the iron-formations were not once continuous, it is conceivable that the two terranes developed separately and were subsequently juxtaposed by tectonic processes.

Structural studies by Holst (1982, 1984, 1985) and Holm and others (1988) have shown conclusively that the southeastern part of the Penokean orogen in Minnesota has undergone an early phase of deformation that was of recumbent style, and that the early, subhorizontal structures of that phase were refolded into upright second-generation folds. These observations are consistent with the presence of nappe structures in the southern terranes, and Holst (1984) has postulated that the brow of a major north-verging nappe lies about 2 km south of Carlton, at a position shown by the long-dashed line on figure 2. Holst's work clearly implies that much of

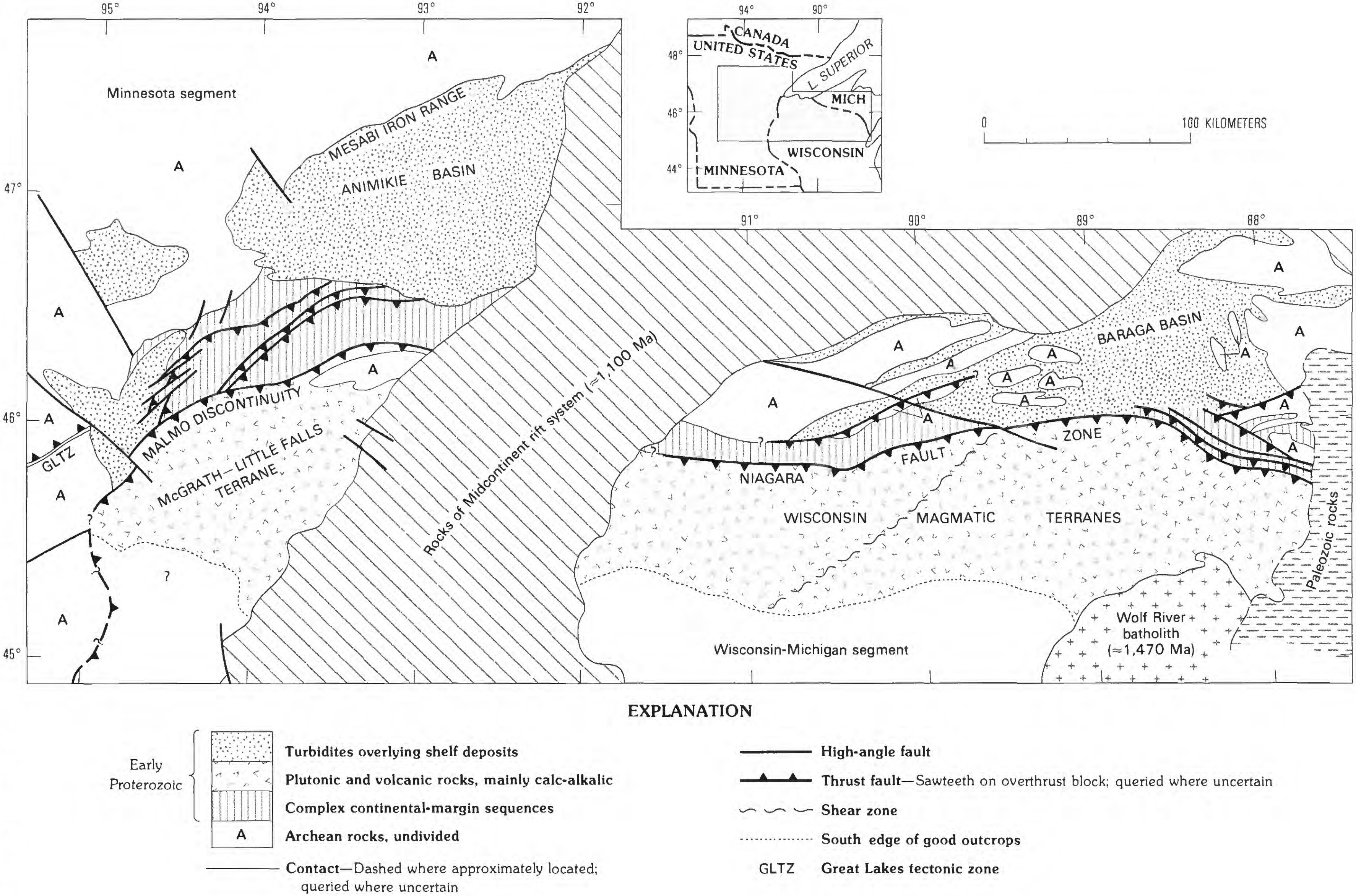

Figure 1. Lake Superior region, showing Penokean orogen (Early Proterozoic) and Midcontinent rift system (Middle Proterozoic). The latter divides the Penokean belt into a Minnesota segment (west of the rift) and a Wisconsin-Michigan segment (east of the rift). In both segments, a complex zone of tectonically imbricated continental-margin rocks lies between a belt of igneous, volcanic, and high-grade metamorphic rocks (on the south) and a series of turbidite basins that overlap Archean basement (on the north). Order of Early Proterozoic map units in explanation is not necessarily their depositional order. Wisconsin-Michigan geology generalized from Sims and others (1989). The term "McGrath–Little Falls *terrane*" has been modified from our earlier term "*structural panel*" (Southwick and others, 1988) to conform with the use of an effective term in broader-published work.

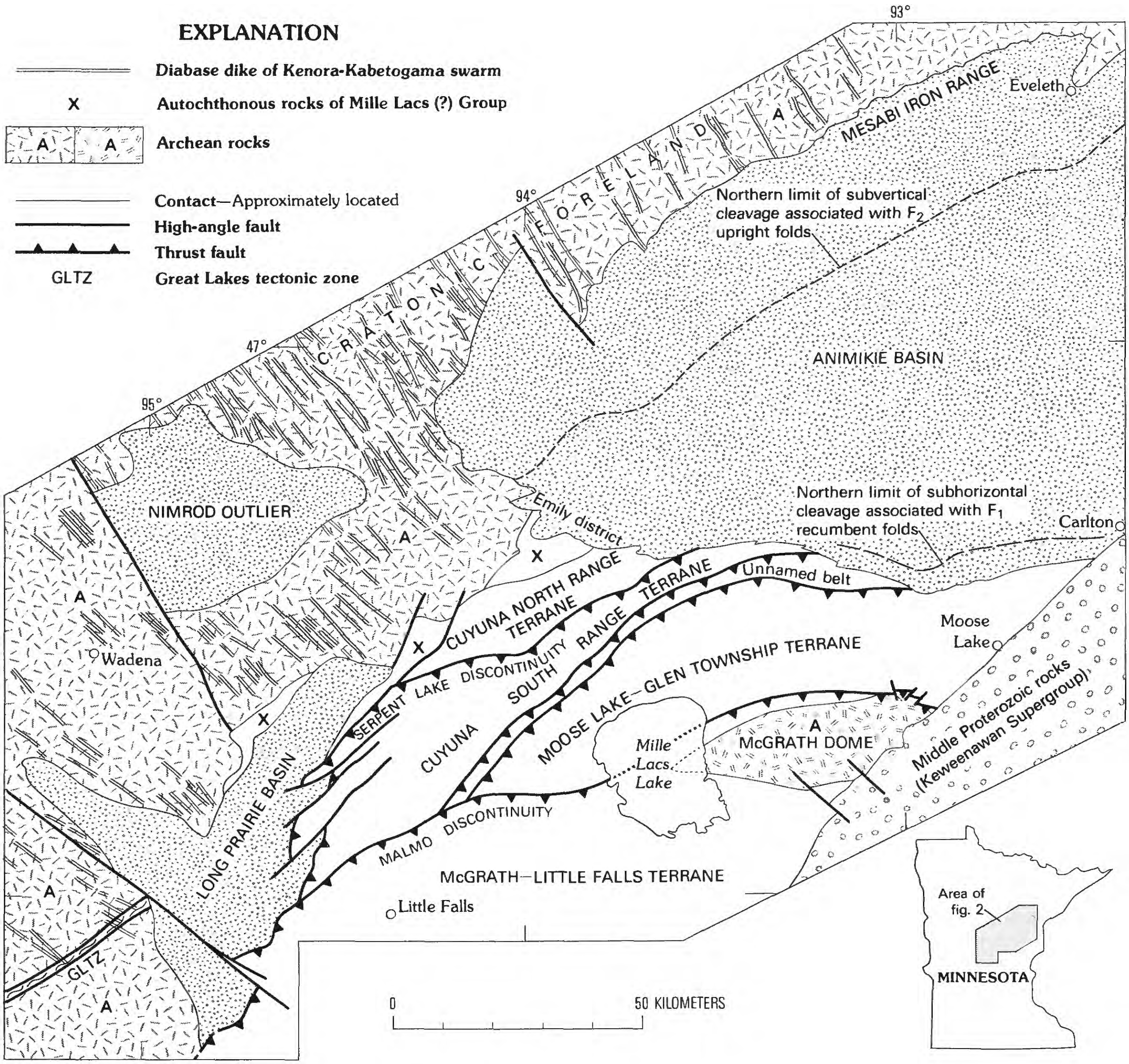

Figure 2. Generalized tectonic map of Penokean orogen in east-central Minnesota, showing major tectonic subdivisions as well as place names mentioned in text. Southern, more complexly deformed (internal) part of orogen consists of four named lithostratigraphic terranes, coupled with a fifth unnamed belt (mostly graphitic schist) between Cuyuna South range and Moose Lake–Glen Township terranes. Internal and medial terranes are bounded by structural discontinuities. Northern, external part of orogen consists of turbidite basins, including main bowl of Animikie basin, Nimrod outlier, and Long Prairie basin. The Animikie and Nimrod probably were once joined. Long-dashed line demarks northern limit of recumbent deformational style as mapped by Holst (1982, 1984) and extended in this study.

the southeastern Penokean terrane in Minnesota may be allochthonous, and opens various plate-tectonic possibilities for interpreting the Minnesota segment of the orogen.

NEW WORK

By 1985 new high-resolution aeromagnetic data were available over all the Penokean orogen in Minnesota (Chandler, 1983a, b, c, 1985). About 80 test holes were drilled in the Penokean area by the Minnesota Geological Survey to substantiate the sources of particular magnetic anomalies and anomaly patterns (Southwick and others, 1986). This drilling was supplemented significantly by the release, in the early 1980's, of a great amount of drill core and related subsurface data that had been acquired by iron mining companies formerly active in the Cuyuna district.

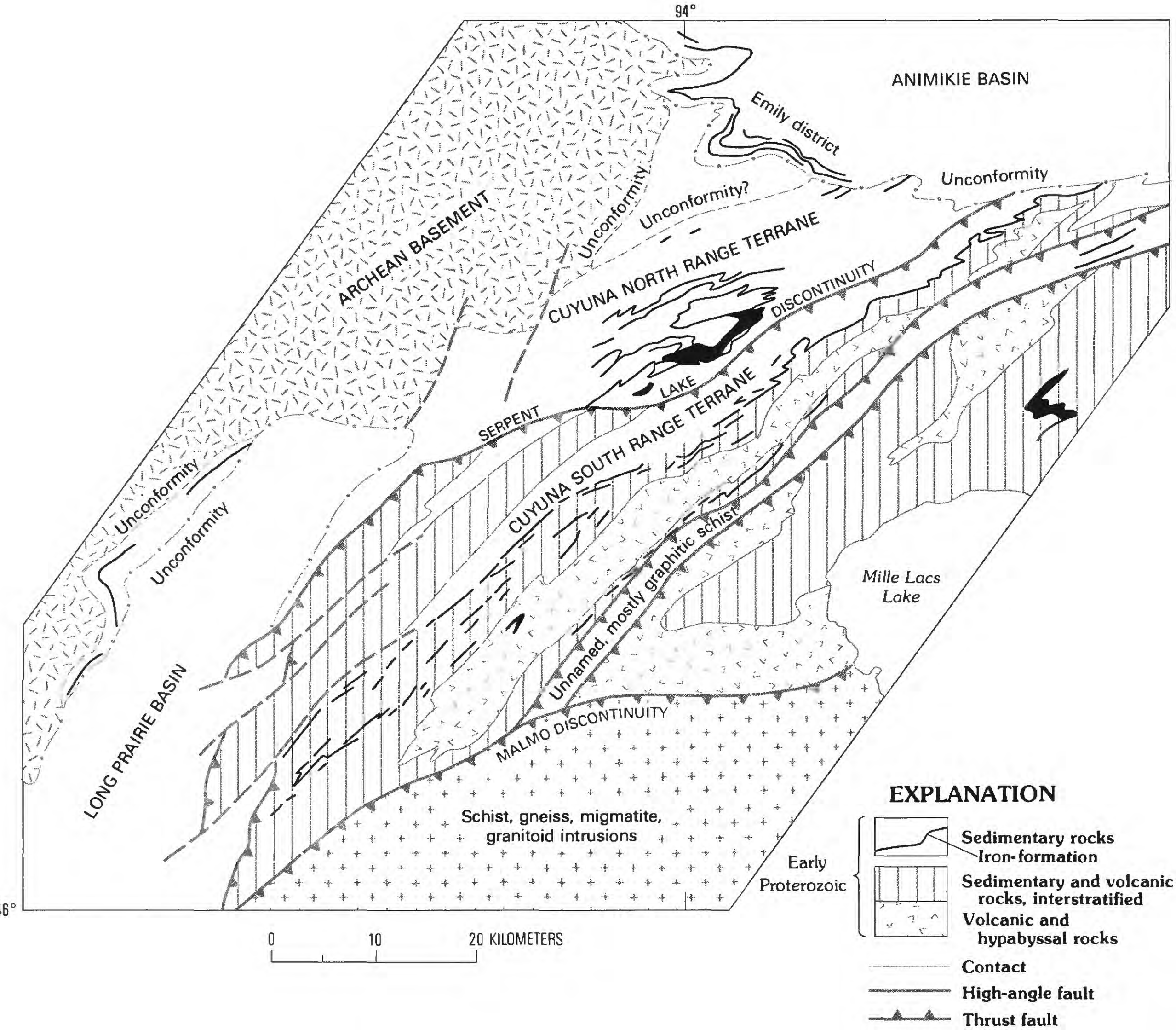

Figure 3. Medial zone of Penokean orogen in Minnesota, including northern part of the strongly deformed fold-and-thrust belt and southern part of the Animikie basin. Dot-dashed line, younger unconformity and approximate basin boundary; dashed line, older unconformity.

Although these company data are largely confined to the immediate neighborhood of magnetic iron-formations that were located decades ago by dip-needle surveys, they provide much stratigraphic and structural information in heavily drift covered areas where virtually no public data were previously available.

The combined approach of regional geophysical analysis, follow-up drilling, and integration of data from outcrop studies and historic drilling led us at an early stage to recognize four major structural discontinuities in the southern part of the orogen (fig. 2). These are defined primarily by map-view geophysical discordances where strike-parallel linear anomaly patterns are abruptly truncated by different linear trends, or where one characteristic anomaly pattern abruptly gives way to another. They are most clearly seen in shaded-relief maps of aeromagnetic data, but also are indicated on contoured aeromagnetic maps, contoured maps of the first vertical derivative of the aeromagnetic data, and contoured maps of the second vertical derivative of the Bouguer gravity anomaly. A published small-scale shaded-relief image that includes the Penokean area (Chandler and others, 1984) illustrates the quality of the aeromagnetic data; the images actually used for interpretation are unpublished, variously enhanced computer plots at scale 1:250,000 and larger.

The drilling and outcrop data suggest that structural discontinuities bound three areas or terranes that are distinct from one another in rock type, stratigraphic rock proportions, metamorphic grade, and structural style. For example, the central two terranes delineated on figure 2 (Moose Lake–Glen Township and Cuyuna South range, together with an unnamed belt between them) contain stratigraphic sequences that include abundant volcanic material, as well as a variety of sedimentary rocks of pelitic to arenaceous affinity (fig. 3). These rocks were metamorphosed chiefly under greenschist-facies conditions and display two generations of cleavage over wide areas. The first cleavage is a shallow-dipping continuous cleavage that varies areally in its distribution and orientation, and is associated with recumbent folds. The second cleavage is most commonly a steeply dipping crenulation cleavage that is associated with inclined to upright small- and meso-scale folds. In contrast, the rocks in the supracrustal sequences in the terrane north of the Serpent Lake discontinuity (fig. 2) contain very little volcanic material. These rocks possess only one slaty cleavage in most areas (two seen locally), and the metamorphic grade is barely of greenschist rank. The contrast is even greater across the Malmo discontinuity (figs. 2, 3), where the low-grade terranes on the north are in contact with the McGrath–Little Falls terrane, of medium- to high-grade schist, gneiss, and migmatite that is shot through with granitoid intrusions.

We interpret the observed geophysical discontinuities to be structural breaks that probably involved brittle-ductile thrust-faulting at shallow crustal levels and the development of mylonite zones at deeper levels. (See Holm and others, 1988, for discussion.) The discontinuities are inferred to dip mainly toward the south, consistent with the sense of northward overturning of folds in the region (Schmidt, 1963; Morey, 1983; Holst, 1982, 1984, 1985), although local reversals of dip are likely. The Werner deconvolution studies of Ferderer (1988a, b) indirectly confirm the general southward (or southeastward) dip; south-dipping slabs or lithologic contacts give the best calculated fits for most of the aeromagnetic profiles analyzed. The Malmo discontinuity was independently defined magnetotellurically by Wunderman and Young (1987) and Wunderman (1988), who deduced it from a major conductive zone that dips southward beneath the McGrath dome (fig. 2). The surface trace of the conductive zone corresponds closely with a profound aeromagnetic discontinuity, and also marks the position of an abrupt change in metamorphic grade of the rocks on either side as previously described.

In previous discussion of the southern part of the Penokean orogen (Southwick and others, 1988), we used the terms "panel" and "structural panel" rather than "terrane" for the tectonostratigraphic entities described above. Those terms were preferred because the dimensions of the entities, the state of knowledge of their internal stratigraphy and external stratigraphic correlations, and the geologic control on the positions and characteristics of their bounding discontinuities were less than adequate for the definition of "terrane" as we understood it. Since then, we have found that the terms "terrane" or "sub-terrane" have been used for many fault-bounded tectonostratigraphic entities that are as small and obscure as those in the Penokean orogen of central Minnesota, and that this usage is permitted by the definitions (Howell and others, 1985, p. 5). Therefore we have changed our terminology to conform with accepted practice.

Our work in the northwestern, more external part of the orogen has demonstrated the existence of two previously unknown turbidite remnants that lie west and southwest of the Animikie basin and that appear similar to the main bowl of the Animikie basin in terms of lithic fill, metamorphic grade, structural pattern, and tectonic setting. The Nimrod outlier (fig. 2) is a patch of essentially flat lying turbiditic material resting on Archean basement, and is analogous to the northernmost, undeformed parts of the Animikie basin. The Long Prairie basin contains turbiditic rocks in which intensity of cleavage development and metamorphic recrystallization increases from northwest to southeast (Southwick, 1987). These observed structural and metamorphic gradients mimic those that occur across the central and southern zones of the main Animikie basin. Geophysical patterns along the southeast margin of the Long Prairie basin strongly imply that the graywacke and slate of the basin fill have been overridden by tectonic slices of volcanic and related rocks of the Cuyuna South range terrane. In addition, a lithic conglomerate near the southeast edge of the Long Prairie basin contains clasts of characteristic South range rocks that indicate a younger age for the Long Prairie fill that can be attributed to a South range source. These observations suggest that the southeast margin of the Long Prairie basin was a dynamic zone of interspersed deposition and thrusting across which northwestward transport brought detritus shed from a tectonic hinterland to the southeast.

Geophysical and drilling data suggest that the sedimentary rocks at the south edge of the main bowl of the Animikie basin rest unconformably above rocks in the structural terranes to the south and southeast (fig. 3). East-northeast-trending aeromagnetic anomalies associated with iron-formations in the Cuyuna North range and Cuyuna South range terranes are sharply truncated by west-northwest-trending anomalies associated with iron-formations that occur in the lower part of the Animikie Group in the Emily iron-bearing district. Severely damped magnetic signals colinear with the truncated Cuyuna district anomalies occur farther northeast, however, and these have been interpreted by Carlson (1985) as arising from Cuyuna-district iron-formations that now are beneath a thick pile of Animikie Group strata. A short distance east of the Emily district (fig. 3), a folded iron-formation of considerable strike length in the Cuyuna South range terrane ends abruptly on the northeast; intensive exploration drilling northeast of the iron-formation terminus encountered gray argillite and graywacke typical of the Animikie Group, rather than the green chloritic phyllite and black carbonaceous slate with which the iron-formation is interbedded along strike to the southwest. These relationships are consistent with unconformable overlapping and burial of the iron-formation-bearing sequence by a younger graywacke-argillite sequence.

The existence and position of the inferred unconformity both become problematical farther east toward Carlton (figs. 2 and 3), where the structural trends in rocks above and below the postulated erosional contact are essentially east-west and parallel (Winchell, 1899; Schwartz, 1942; Holst, 1984). Outcrop mapping and drilling show that an abrupt transition, if not a sharp contact, occurs between contrasting supracrustal rock sequences along the inferred unconformity trace, but they do not prove an unconformity. Mineralogical and geochemical contrasts across the transition zone strengthen the case, however (Southwick and others, 1988), and these data, together with the geophysical evidence along strike to the west, provide a circumstantial argument for extending the unconformity as mapped (fig. 3).

The inferences of a thrust-faulted boundary at the southeast edge of the Long Prairie basin (fig. 3) and an unconformable boundary at the south edge of the Animikie basin might appear to be incompatible. They can be reconciled, however, if the rocks within the Long Prairie and Animikie basins are viewed as tectonically equivalent but temporally somewhat diachronous, or if the latest thrust motion on the Serpent Lake discontinuity was confined to the west half of its length. Either of these possibilities is quite conceivable in dynamic environments associated with convergent tectonism near zones of subduction.

TECTONIC CONCLUSIONS AND STRATIGRAPHIC IMPLICATIONS

We regard the southern part of the Penokean orogen in Minnesota as a fold-and-thrust belt made up of four major structural terranes. The McGrath–Little Falls terrane contains relatively high grade schist and gneiss, a mantled gneiss dome that is cored by multiply deformed Archean gneiss (Holm and others, 1988), and several late-tectonic to post-tectonic granitoid plutons (fig. 2). Taken as a whole, the McGrath–Little Falls terrane has the attributes of a deep-seated crustal slice that has been elevated by tectonic imbrication. It is interpreted to occupy an internal position within the Penokean orogen. To the north of the McGrath–Little Falls terrane, the Moose Lake–Glen Township and Cuyuna South range terranes both contain folded volcanic and sedimentary rocks of variable but generally low metamorphic grade (McSwiggen, 1987; Morey, 1978). These two terranes are separated from each other by a long, arcuate zone of probable thrusting that is localized by a belt of weak and highly deformed graphitic schist. Both terranes contain much more mafic to intermediate volcanic and hypabyssal rock than was portrayed on earlier geologic maps (for example, compare Morey and others (1981) with Southwick and others (1988)). In addition, they contain abundant metapelite, metasiltite, and graphitic argillite, many thin, lensoidal units of iron-formation (Morey and Morey, 1986), and poorly known amounts of quartzite and related arenaceous rocks. All these rocks are closely folded and cleaved, and locally show evidence of multiple fold generations (Holst, 1982, 1984, 1985). Taken as a whole, the Moose Lake–Glen Township and Cuyuna South range terranes have the attributes of a medial tectonic zone dominated by fold-and-thrust deformation. Northwest of these terranes, the Cuyuna North range terrane contains weakly metamorphosed, less strongly deformed sedimentary rocks. Volcanic rocks are volumetrically minor. The main stratigraphic units include a thick lower section of metapelite and metasiltite, a medial section dominated by iron-formation units that define a complex synclinorium near the center of the terrane, and an upper unit that consists of dark-colored, graphitic argillite and siltite with local interbeds of ferruginous chert. Taken as a whole, the Cuyuna North range terrane has the attributes of a small restricted basin that was incorporated tectonically in the more external part of a fold-and-thrust belt. Additional details on the geology of the terranes in the fold-and-thrust belt are presented in Southwick and others (1988).

The fold-and-thrust belt abuts, and is partially overlapped by, a complex turbidite-filled sedimentary basin lying to the northwest (the Animikie basin and its smaller analogs). The Archean basement beyond and beneath the northwest flanks of the turbidite basins constitutes the cratonic foreland against which northwest-directed tectonic imbrication is thought to have occurred.

Sedimentary strata of the Animikie Group rest with unequivocal unconformity on the Archean craton on the northwest side of the Animikie basin, and with inferred unconformity on previously deformed rocks of the fold-and-thrust belt on the southeast side. Rocks of the Animikie Group near the southern flank of the basin were folded when the underlying rocks were refolded during the later stages of regional compression (Southwick and others, 1988), whereas they were scarcely deformed at all on the cratonal, northern flank. Sedimentary fill in the basin decreases in total thickness

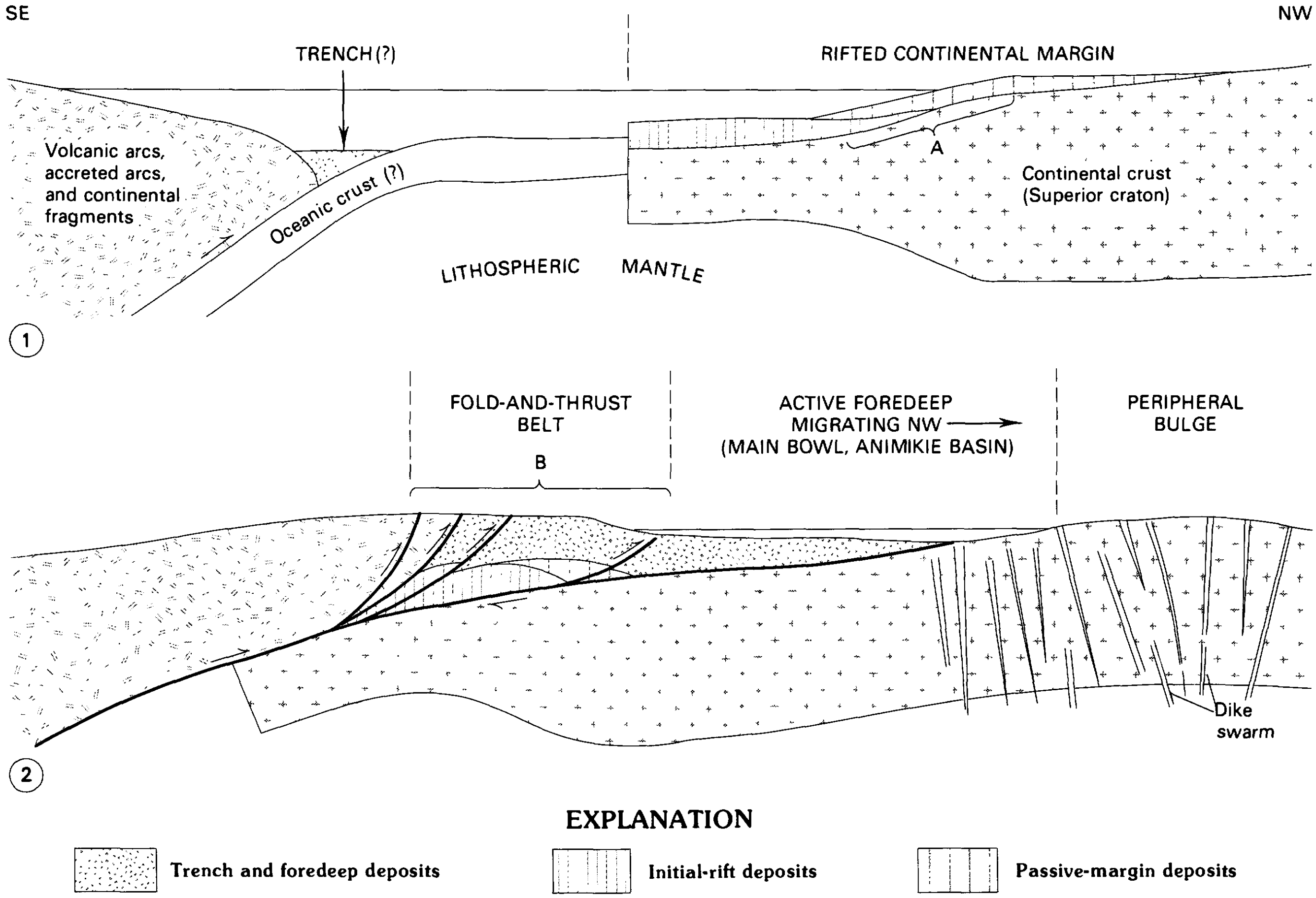

Figure 4. Schematic diagram modified from Hoffman (1987) illustrating the evolution of an oceanic trench (stage 1) into a foredeep (stage 2). A, passive-margin deposits accumulating on continental edge; B, location of fold-and-thrust belt involving volcanic and sedimentary rocks and their basement.

and in degree of low-grade metamorphism from southeast to northwest. Primary sedimentary structures in rocks near the rim on the north side of the basin clearly indicate a northern (cratonal) source, whereas the sedimentological and geochemical attributes of at least some of the lithic graywacke near the southern basin margin are consistent with a southern provenance (Southwick and others, 1988, p. 7–9 and 16). Taken as a whole, the broad features of the Animikie basin and its smaller analogs are consistent with those of a migrating foredeep produced by tectonic loading and downbowing of continental crust during attempted subduction of an Archean continental margin. Our conceptual model for the formation of the basin accords well with the general foredeep model developed by Price (1973), Beaumont (1981), Jordan (1981), and Quinlan and Beaumont (1984), and as developed more fully for Proterozoic orogens in North America by Hoffman (1987). Figure 4 summarizes our general views for the origin of the Animikie basin as a migrating foredeep.

With respect to the Minnesota segment of the Penokean orogen, stage 1 of figure 4 represents the rifted margin of the Superior craton approaching a southeast-dipping subduction zone in Early Proterozoic time. Initial-rift deposits, including the volcanic rocks of the Mille Lacs Group, are riding on the continental edge; passive-margin deposits, possibly preserved as quartzose sedimentary rocks of the Mille Lacs Group, are accumulating near A. Stage 2 of figure 4 represents active subduction of the continental margin. Crustal loading by the ensuing fold-and-thrust mass has occurred, generating as a flexural response an actively migrating foredeep (main bowl of the Animikie basin) on the continental side. Various volcanic and sedimentary rocks and their stratigraphic basement are involved in fold-and-thrust nappes near B, representing elements such as island arcs, accretionary wedge deposits, and continental fragments that have been swept together tectonically. The marginal deposits from stage 1, as well as early deposits laid down toward the rear of the foredeep, also may be incorporated in the deforming mass; these appear to be dominant in the Penokean imbricate stack in Minnesota as preserved in the region from the Malmo discontinuity to the south margin of the Animikie basin (fig. 2). No oceanic crust, trench deposits, or volcanic rocks of arc affinity have been identified positively in Minnesota, although Horan and others (1987) suggested that an isolated gabbro body near Mora, in the McGrath–Little Falls terrane (fig. 2), has oceanic attributes.

Although we are relatively confident that the principal collisional event (or events) in the Penokean orogen in Minnesota involved subduction of an Archean craton beneath a northwest-transported fold-and-thrust mass, and the consequent development of a migrating foredeep, serious uncertainties exist regarding the tectonic setting and age of the supracrustal rocks in the fold-and-thrust mass, as well as the timing of subduction.

We first consider evidence that pertains to the tectonic setting and age of the supracrustal rocks in the fold-and-thrust belt. Despite the stratigraphic uncertainties introduced by complex structure, tectonic shuffling, and poor outcrop, it does appear that in a broad way the lower parts of the Mille Lacs Group are mainly quartzose sedimentary rocks, volcanic rocks, graphitic slate, and iron-formation, whereas the upper parts are mainly pelitic and semipelitic slate and phyllite with lenses of iron-formation and volcanic rock (Morey, 1978, 1983). Collectively these rocks resemble parts of the Early Proterozoic Chocolay Group and overlying Menominee Group in Upper Michigan (Cannon, 1986, and references therein). Rocks of the Chocolay Group vary abruptly in thickness and stratigraphic composition over short distances, and have been interpreted (Larue, 1981, 1983) as accumulations in an extensional environment, possibly within local rift basins and on the interbasin platforms that developed along a foundering continental margin. Morey (1978, 1983) has interpreted the general stratigraphic relationships within the presumably lower parts of the Mille Lacs Group in approximately the same way.

The geochemistry of the volcanic rocks in the Mille Lacs Group further supports an extensional setting. Both tholeiitic and calc-alkalic compositions are represented (fig. 5), but the tholeiitic compositions greatly predominate. Furthermore, the compositions of volcanic rocks largely avoid the "orogenic" field in the Al_2O_3-FeO-MgO discrimination diagram of Pearce and others (1977) and the "island-arc basalt" field in the Zr:Y versus Zr diagram of Pearce and Norry (1979) (figs. 6 and 7). These data suggest that island-arc volcanic assemblages probably were not significant constituents of the tectonic mass now present in the deeply eroded fold-and-thrust belt. Rather, the basalts have a "within-plate" or "continental" affinity consistent with a continental-

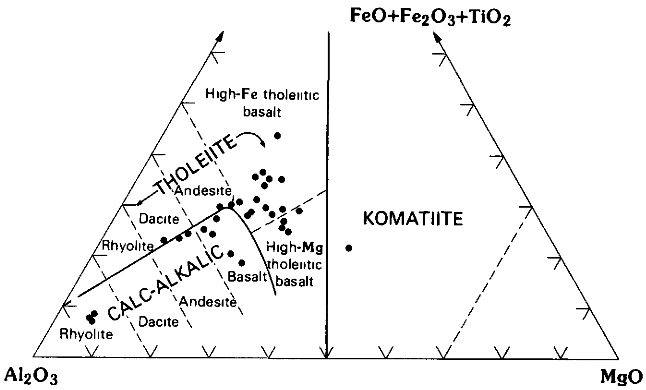

Figure 5. Jensen plot (Jensen, 1976) of volcanic rock compositions from various parts of fold-and-thrust belt. Includes metamorphosed lavas, hypabyssal intrusions, and fragmental volcaniclastic rocks ranging from 45 to 72 weight percent SiO_2.

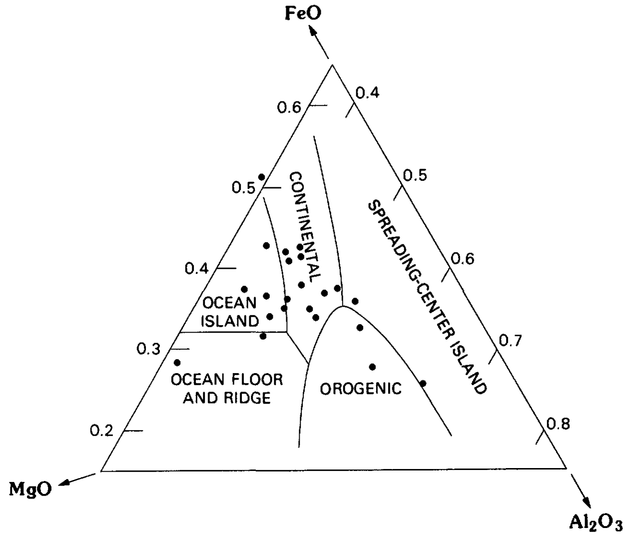

Figure 6. FeO-MgO-Al_2O_3 plot of Pearce and others (1977) showing distribution of basaltic rock compositions from fold-and-thrust belt. FeO refers to total Fe reported as FeO. Data in weight percent. Note sparsity of points in orogenic field.

margin genesis. Rare-earth element plots for Mille Lacs volcanic rocks (fig. 8) show moderate LREE enrichment and no Eu anomaly. Although this REE pattern is not diagnostic of tectonic setting, it is consistent with the observed patterns for continental tholeiites reported by Dupuy and Dostal (1984), and therefore is consistent with a rifted-margin genesis.

Beck (1988) obtained a Sm:Nd isochron age of 2,197±39 Ma for a suite of six basalt and diabase samples from the Mille Lacs Group in the Moose Lake–Glen Township structural terrane. This isochron age is very close to the model age of 2,199 Ma based on an

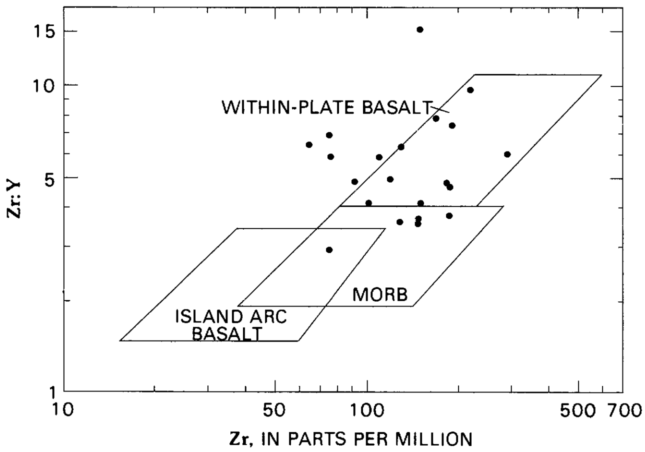

Figure 7. Zr:Y plotted against Zr, from Pearce and Norry (1979), showing distribution of basaltic rock compositions from fold-and-thrust belt. Note virtual absence of points from island-arc field. MORB, mid-ocean ridge basalt.

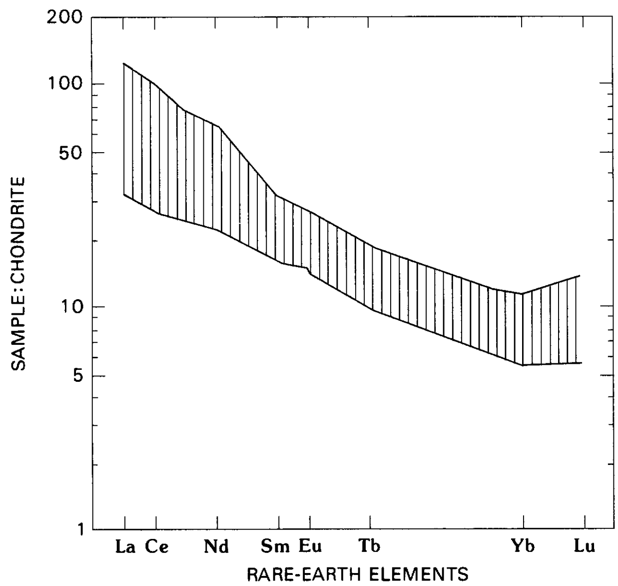

Figure 8. Chondrite-normalized rare-earth element plots for basaltic rocks of fold-and-thrust belt. Includes unpublished data provided by K.J. Schulz, U.S. Geological Survey.

initial ε Nd value of 2.84±0.26 for the samples and the neodymium mantle evolution curve of Albarede and Brouxel (1987), and thus the isochron age is probably close to the crystallization age of the rocks. Rb:Sr investigations of the same samples yield an errorchron age of 1,746±86 Ma (Beck, 1988) that may be related to metamorphism and hydrothermal activity associated with the latest stages of regional compression and the crustal response to tectonic thickening, uplift, cooling, and unroofing (Dewey and others, 1970; Haxby and Turcotte, 1976; Peterman and Sims, 1988). Taken together, the Sm:Nd and Rb:Sr isotopic data suggest that some of the volcanic rocks now in the fold-and-thrust belt were extruded at about 2,200 Ma and compressionally reassembled into nappes prior to about 1,740 Ma.

The next question is when, and for how long, subduction occurred, and, relatedly, the age of the turbiditic rocks in the Animikie basin. Goldich and Fischer (1986) reported a U-Pb zircon age of 1,982±5 Ma for a tectonized granite gneiss within the core complex of the McGrath Gneiss of the McGrath dome (fig. 2). Goldich and Fischer interpreted the granite gneiss as an Early Proterozoic pluton that was emplaced into the Archean McGrath Gneiss and later deformed, and they regarded the reported age as a crystallization age, even though metamorphic disturbance of the U-Pb systematics cannot be ruled out. In the same report, Goldich and Fischer also gave a U-Pb zircon age of 1,869±5 Ma for a tonalite gneiss (Bradbury Creek Granodiorite of Morey, 1978) that is a syntectonic pluton emplaced into polygenetic migmatite (Hillman Migmatite of Morey, 1978) in the west-central part of the McGrath–Little Falls structural terrane (fig. 2). The reported age is interpreted as a crystallization age (Goldich and Fischer, 1986). It corresponds well with a Rb:Sr metamorphic age of 1,850 Ma from strata in the Cuyuna North range terrane, and with the crystallization age of 1,850±30 Ma from several syntectonic Penokean plutons in Wisconsin (Van Schmus, 1980). Other syntectonic intrusions of tonalite, granodiorite, and granite structurally akin to the Bradbury Creek Granodiorite were emplaced into the Hillman during the Penokean (Morey, 1978), but these have not been studied isotopically.

The post-orogenic Rockville and Reformatory Granites of Morey (1978) that occur mainly within the McGrath–Little Falls structural terrane and poorly mapped terrane farther southwest (fig. 3) yield U-Pb crystallization ages of 1,812±9 Ma (S.S. Goldich, cited in Horan and others, 1987). Other post-orogenic plutons, such as the St. Cloud Granite, yield a minimum U-Pb age of 1,770 Ma (Spencer and Hanson, 1984). Although most of the St. Cloud Granite plutons occur in the southern, tectonically deeper parts of the orogen, a few minor stocks and plugs petrographically identical to those in the southern area do occur in more external zones, where they appear to pierce and "pin" the imbricate stack. We conclude, therefore, that tectonic stacking had ceased prior to about 1,770 Ma, and it may have stopped long before that.

Rb:Sr studies yield an errorchron age of 1,741±18 Ma for one of the 1,770-Ma St. Cloud Granite plutons (S.S. Goldich, cited in Horan and others, 1987). This age accords approximately with Rb:Sr ages in the interval of 1,750 to 1,740 Ma for rocks in zones of brittle to semi-brittle cataclasis within the McGrath Gneiss

(Keighin and others, 1972), an age of 1,730 Ma for metamorphic recrystallization in the southern part of the Animikie basin (Peterman, 1966, as recalculated by Keighin and others, 1972), and one of 1,746 Ma for hydrothermal reequilibration in volcanic rocks of the Mille Lacs Group (Beck, 1988). As previously stated, we consider the Rb:Sr events clustered loosely around 1,740 Ma to be caused by uplift-related phenomena.

To summarize, the available isotopic data suggest that rocks in the southern part of the fold-and-thrust belt were undergoing magmatism, and possibly deformation, as early as 1,982 Ma. Deformation was under way at 1,869 Ma, when the syntectonic Bradbury Creek Granodiorite was emplaced, and had ceased by 1,770 Ma, when the post-tectonic St. Cloud Granite was emplaced into the fold-and-thrust mass. Uplift, erosion, and cooling were under way by about 1,740 Ma.

If the foregoing interpretation of geochronologic data is correct, subduction-driven thrusting and foredeep development could have started any time after the eruption of continental-margin volcanic rocks at about 2,200 Ma, and they probably were well under way by 1,982 Ma, when the earliest granitoid plutonism was occurring. On the other hand, we cannot rule out a later onset of foredeep development (say, 1,870 Ma). Foredeep sedimentation may well have continued for an extended period of time as basins formed, were partly consumed, and were succeeded by other basins in response to attempted subduction of the cratonic foreland. Turbidite wedges of several different ages may very well constitute the fill of the Animikie basin, and turbiditic rocks presently exposed along the south margin of the basin are in no way required to be time-correlative with those along the north margin. On the northwest side of the basin, northwest of the Mesabi iron range (fig. 2), basal units of the Animikie Group unconformably truncate a swarm of diabase dikes in the foreland that are dated at 2,125±45 Ma by a whole-rock Rb:Sr isochron (Southwick and Day, 1983; Southwick and Halls, 1987; Beck, 1988). This dike age is a maximum limit for the onset of sedimentation on the north rim of the basin, but sheds no light on the actual time (or times) during which sedimentation occurred thereafter.

The unconformable southern contact of the Animikie basin against previously folded rocks of the Cuyuna district precludes correlation of the Biwabik Iron-formation in the Animikie basin with the Trommald Formation in the Cuyuna North range terrane. Furthermore, that the Trommald and other iron-formation units in the Cuyuna North range terrane correlate with the iron-formation units in the Cuyuna South range terrane is by no means certain. Besides being separated from each other by the Serpent Lake structural discontinuity, the iron-formations of the two terranes differ substantially in facies, geochemistry, and stratigraphic associations. The iron-formation of the South range terrane is mainly of sulfide, carbonate, and silicate facies and was deposited as lenticular masses and thin layers in close stratigraphic proximity to mafic volcanic rocks and euxinic black shale (Morey and Morey, 1986; Southwick and others, 1988). The iron-formations of the Cuyuna North range terrane have more blanketlike morphology, are interbedded with dark-colored argillite and siltite, and are predominantly of carbonate and oxide facies. They also are enriched geochemically in manganese and phosphorus as compared to the iron-formations in either the Cuyuna South range terrane or the Animikie basin.

Therefore it appears that iron-formations were deposited in three distinct geologic environments during the evolution of the Penokean orogen. Iron sedimentation occurred in close association with mafic volcanism under euxinic depositional conditions, probably at an early stage in the tectonic evolution of the orogen, and the rocks of this episode now reside in the folded and thrust-faulted domain of the two central structural terranes. Iron-formations of this type constitute unnamed units within the Mille Lacs Group of Morey (1978). The Trommald and associated iron-formation units of the Cuyuna North range terrane were deposited in close association with carbonaceous, argillaceous, and locally calcareous muds in a small basin that was ancestral to the North range synclinorium. The well-established and distinctive stratigraphic sequence on the North range, defined informally as the "North range group" by Southwick and others (1988), is called the North range sequence in subsequent discussion. Finally, a third episode of iron sedimentation occurred on the cratonic rim of the main bowl of the Animikie basin at a later time in the history of the orogen. The iron-formations of this generation, units traditionally assigned to the Animikie Group, were deposited in association with tidalites on a well-oxygenated to moderately oxygenated shallow marine shelf (Ojakangas, 1983). Units of this type include the Biwabik Iron-formation of the Mesabi range and the thin units of equivalent stratigraphic position in the Emily district in the southwestern part of the basin. Figure 9 illustrates the inferred stratigraphic relationships among Early Proterozoic units of group rank in east-central Minnesota.

REGIONAL CONSIDERATIONS

The inference of subduction-driven horizontal tectonism in the Minnesota segment of the Penokean orogen fits broadly with recent plate-tectonic interpretations in Michigan and Wisconsin (Sims and Peterman, 1983; Larue, 1983; Morey, 1983; LaBerge and Myers, 1984; Larue and Ueng, 1985; Sims, Peterman,

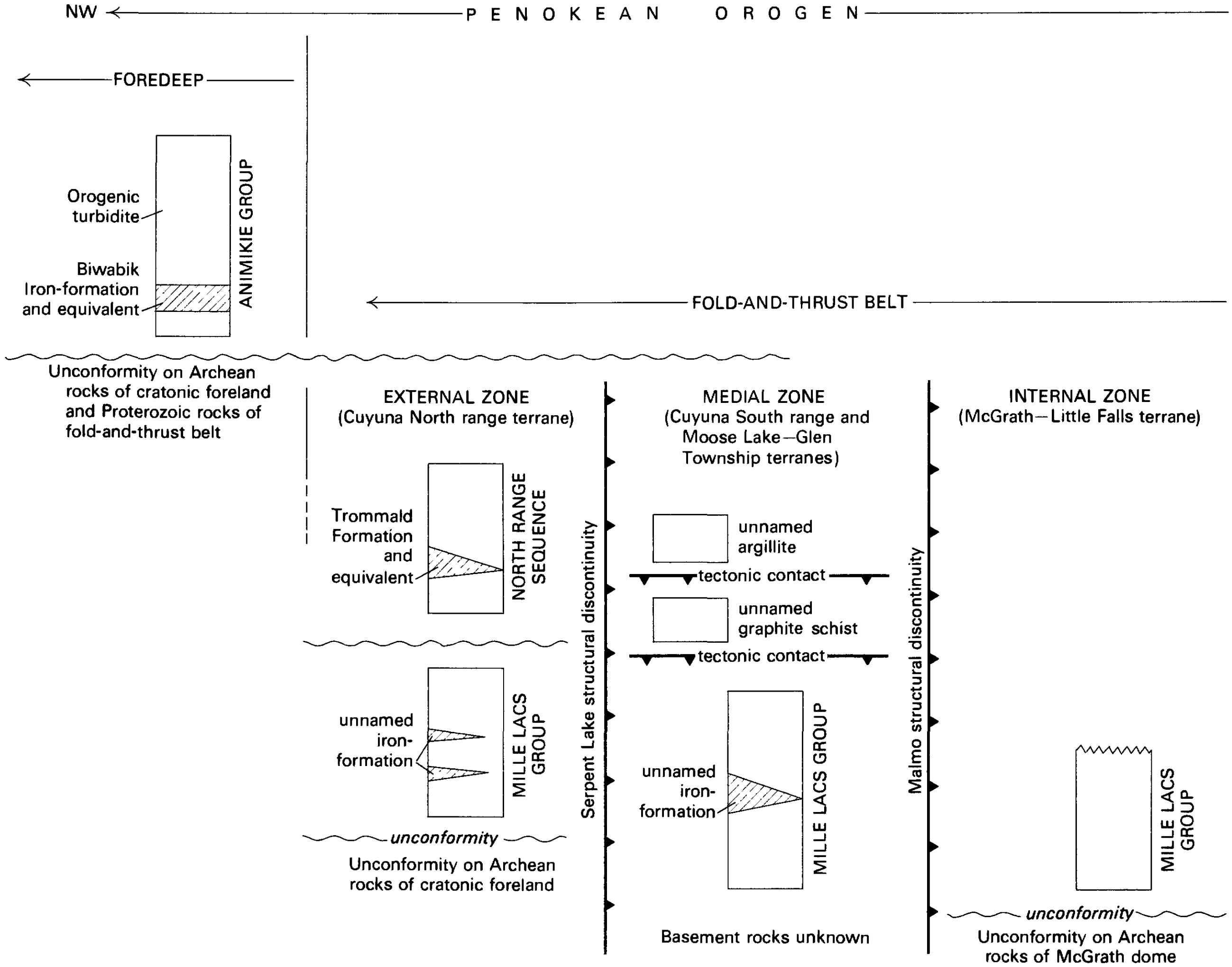

Figure 9. Inferred stratigraphic relationships among rock units in Minnesota segment of the Penokean orogen. Width of orogen is approximately 100 km. Modified from Southwick and others (1988).

and Schulz, 1985; Sims, Peterman, Klasner, and others, 1987; Schulz, 1987). Although the Minnesota interpretation put forward here does differ in several respects from the described geology to the east, and raises questions as to how the two segments of the orogen might correlate in detail across the Midcontinent rift, the general tectonic framework of both areas is consistent (fig. 1).

Possible Equivalence of Niagara Fault Zone and Malmo Discontinuity

In Michigan and Wisconsin, the Niagara fault zone is a tectonic suture between rocks of cratonic affinity on the north and rocks of island-arc affinity on the south (Larue, 1983; Larue and Ueng, 1985; Sims, Peterman, and Schulz, 1985; Sedlock and Larue, 1985). The predominantly igneous suite of rocks south of the Niagara fault zone, which includes both volcanic and intrusive constituents, yields crystallization ages clustered near 1,870 Ma (Banks and Rebello, 1969, recalculated; Van Schmus, 1976, 1980; Van Schmus and Bickford, 1981; Afifi and others, 1984; Beck, 1988; Sims and others, 1989). In Minnesota, neither a suture zone analogous to the Niagara fault zone nor a suite of arc-related 1,870-Ma volcanic rocks has yet been identified positively. However, the structural terrane south of the Malmo discontinuity contains a number of calc-alkaline intrusive rocks that are comparable in geochemistry and age to arc-related plutons in the magmatic terranes south of the Niagara fault zone in Wisconsin (Horan and others, 1987), and therefore the Malmo and Niagara zones may correlate across the Midcontinent rift. This correlation is further suggested by the magnetotelluric anomalies associated with the Malmo zone in Minnesota (Wunderman and Young, 1987) and the Niagara zone in northwestern Wisconsin (Flambeau anomaly of Sternberg and Clay, 1977). Upon removal of about 60 km of extension on the intervening Midcontinent rift (Chandler, 1983d), the magnetotelluric features become essentially colinear.

The Malmo discontinuity becomes difficult to trace with assurance in south-central Minnesota, but it most probably swings from east to northeast to an approximately north-south orientation (fig. 1). This is suggested by the oroclinal bend of structural trends from west to southwest in the fold-and-thrust belt and the continuing southward deflection of geophysical trends into poorly mapped terrane south of the area we have studied. Work is currently under way in that region.

Correlation of Stratigraphic Sequences North of Niagara-Malmo Zone—Possibilities and Problems

The volcanic rocks of cratonic affinity north of the Niagara fault zone in Michigan and Wisconsin (Ueng and others, 1988; Beck, 1988) are associated with sedimentary rocks that have attributes suggesting continental-margin and early-rift depositional environments (Larue, 1981; Sedlock and Larue, 1985). In those respects they resemble volcanic rocks in the fold-and-thrust belt of the Penokean orogen in Minnesota, but age data do not agree between the two areas. Isotopic studies of rocks from the Mille Lacs Group in the Moose Lake–Glen Township terrane of Minnesota yield ages some 300 m.y. older than the 1,910±10 Ma age for the geochemically similar metabasalts of the Hemlock Formation in the Menominee Group of Upper Michigan (Van Schmus, 1976; Van Schmus and Bickford, 1981; Beck, 1988). In terms of classic stratigraphy, the interval from 2,197±39 Ma to 1,910±10 Ma may represent the span of deposition for strata in the Lake Superior region that are older than the Animikie Group in Minnesota.

Although the age disparity and a number of other stratigraphic uncertainties must be resolved before regional correlations can be entertained, the broad similarities between the Iron River–Crystal Falls–Marquette area of Michigan (Cannon, 1986) and the fold-and-thrust terrane in east-central Minnesota suggest a tectonic linkage. Both are terranes of tectonically imbricated "continental" rocks that abut large turbidite basins on the north. The turbidite basins in both areas are framed by, and lie unconformably upon, Archean cratonic basement along their north margins. The stratigraphy, sedimentology, and structural styles of the Animikie Group in the Animikie basin of Minnesota and the Baraga Group in the Baraga basin of Michigan are strikingly similar on the regional scale (Morey, 1983, and references therein) and are compatible in both cases with a foredeep depositional setting for the rocks (Hoffman, 1987).

Because the Penokean foredeeps would have developed and filled under dynamic conditions, the turbiditic sedimentary rocks they contain should provide a record of changing slope conditions, current regimes, and provenance as a function of time, especially near their south margins. Such a record of depositional complexity has been deduced on isotopic grounds for the south margin of the Baraga basin (Barovich and others, 1989). It follows that cryptic unconformities between physically similar turbidite wedges of differing age should be expected in the Penokean foredeeps (see Robertson, 1987, for an illustrative Phanerozoic example), but none has yet been demonstrated. Although cryptic unconformities will be difficult to demonstrate, owing to the lack of marker beds and critical outcrops, the possibility of their existence should guide future stratigraphic field work in the Animikie and Baraga basins and be factored into tectonostratigraphic reconstructions.

In a previous section, we pointed out that Early Proterozoic iron-formations in Minnesota occur in stratigraphic association with volcanic rocks and black shales in the Mille Lacs Group, with laminated siltite and pelite in the North range sequence, and with tidally deposited arenite and siltite in the basal part of the Animikie Group. These lithostratigraphic associations are broadly similar to those in the Iron River–Crystal Falls area of Michigan where the main iron-formations are associated with volcanic rocks of the Menominee Group, with various fine-grained argillaceous rocks in the Paint River Group (Cannon, 1986, and references therein), and with tidalites in the lower part of the Baraga Group (R.W. Ojakangas, oral commun., 1989). However, the currently defined stratigraphic order in Michigan places the Paint River Group as the youngest of these, whereas the lithologically analogous North range sequence is not the youngest group-rank unit in the inferred Minnesota stratigraphic section. This disparity may mean that the inferred stratigraphic order is wrong in either Michigan (Cambray, 1987) or Minnesota, or that the association of iron-formations with argillaceous strata was repeated within the stratigraphic section.

Summary

Penokean convergence appears to have been driven by south- or southeast-directed subduction of Archean craton beneath tectonically imbricated terranes built of continental-margin, island-arc, and perhaps some back-arc rocks. The imbricate mass in Minnesota contained mainly continental-margin rocks along with possible back-arc material (Southwick and others, 1988), whereas in Michigan and Wisconsin it consisted of both continental-margin and island-arc rocks. The imbrication process undoubtedly was complex in space and time, and led to variations along strike in the composition and subsequent history of the accreted mass. No matter what the exact character of the load was, however, the tectonic imbrication and crustal loading produced migrating foredeeps on downbowed continental crust to the north and northwest of the main tectonic zone.

In Minnesota, we infer that deposition of the pre-collisional Mille Lacs Group occurred in the interval 2,197–1,910 Ma. Deformation, metamorphism, and plutonism were under way as early as about 1,982 Ma and culminated about 1,870 Ma, when voluminous syntectonic plutons were emplaced. Crustal downflexure and foredeep development may have begun prior to the onset of extensive plutonism and persevered for a long period of time. Early foredeeps (such as the ancestor to the Cuyuna North range synclinorium) eventually were overridden and incorporated in the imbricate thrust stack. Later foredeeps, including the Animikie basin, followed in turn as subduction continued and then waned. A second regional episode of deformation and metamorphism accompanied the emplacement of late-tectonic to post-tectonic intrusions in the interval 1,820(?) to 1,770 Ma; structures primarily of this generation developed in rocks of the Animikie Group and are overprinted on earlier structures in older rocks. Isostatic uplift is inferred to have culminated by about 1,740 Ma.

REFERENCES CITED

Afifi, A., Doe, B.R., Sims, P.K., and Delevaux, M.H., 1984, U-Th-Pb isotope chronology of sulfide ores and rocks in the Early Proterozoic metavolcanic belt of northern Wisconsin: Economic Geology, v. 79, p. 338–353.

Albarede, F., and Brouxel, M., 1987, The Sm/Nd secular evolution of the continental crust and the depleted mantle: Earth and Planetary Science Letters, v. 82, p. 25–35.

Andrews, A.J., Masliwec, A., Morris, W.A., Owsiacki, L., and York, D., 1986, The silver deposits of Cobalt and Gowganda, Ontario, II—An experiment in age determinations employing radiometric and paleomagnetic measurements: Canadian Journal of Earth Sciences, v. 23, p. 1507–1518.

Banks, P.O., and Rebello, D.P., 1969, Zircon ages of a Precambrian rhyolite, northeastern Wisconsin: Geological Society of America Bulletin, v. 80, p. 907–910.

Barovich, K.M., Patchett, P.J., Peterman, Z.E., and Sims, P.K., 1989, Nd isotopes and the origin of 1.9–1.7 Ga Penokean continental crust of the Lake Superior region: Geological Society of America Bulletin, v. 101, p. 333–338.

Beaumont, C., 1981, Foreland basins: Geophysical Journal, v. 65, p. 291–329.

Beck, J.W., 1988, Implications for Early Proterozoic tectonics and the origin of continental flood basalts, based on combined trace element and neodymium/strontium isotopic studies of mafic igneous rocks of the Penokean Lake Superior belt, Minnesota, Wisconsin and Michigan: Minneapolis, Minn., University of Minnesota Ph. D. dissertation, 262 p.

Cambray, F.W., 1987, An alternate stratigraphic correlation within the Marquette Range Supergroup, N. Michigan: Geological Society of America Abstracts with Programs, v. 19, p. 192.

Cannon, W.F., 1986, Bedrock geologic map of the Iron River 1°×2° quadrangle, Michigan and Wisconsin: U.S. Geological Survey Miscellaneous Investigations Map I–1360–B, scale 1:250,000.

Card, K.D., and Ciesielski, A., 1986, DNAG #1, Subdivisions of the Superior Province of the Canadian Shield: Geoscience Canada, v. 13, p. 5–13.

Carlson, K.E., 1985, A combined analysis of gravity and magnetic anomalies in east-central Minnesota: Minneapolis, Minn., University of Minnesota M.S. thesis, 138 p.

Chandler, V.W., 1983a, Aeromagnetic map of Minnesota, St. Louis County: Minnesota Geological Survey Aeromagnetic Map Series A–2, scale 1:250,000, 2 pls.

______ 1983b, Aeromagnetic map of Minnesota, Carlton and Pine Counties: Minnesota Geological Survey Aeromagnetic Map Series A–3, scale 1:250,000, 2 pls.

______ 1983c, Aeromagnetic map of Minnesota, east-central region: Minnesota Geological Survey Aeromagnetic Map Series A–4, scale 1:250,000, 2 pls.

______ 1983d, Correlation of magnetic anomalies in east-central Minnesota and northwestern Wisconsin—Constraints on magnitude and direction of Keweenawan rifting: Geology, v. 11, p. 174–176.

______ 1985, Aeromagnetic map of Minnesota, central region: Minnesota Geological Survey Aeromagnetic Map Series A–5, scale 1:250,000, 2 pls.

Chandler, V.W., Norstrand, E., and Anderson, S., 1984, Shaded-relief aeromagnetic anomaly map of northeastern and east-central Minnesota: Minnesota Geological Survey Miscellaneous Map M–53, scale 1:1,000,000.

Dewey, J.F., McKerrow, W.S., and Moorbath, S., 1970, The relationship between isotopic ages, uplift, and sedimentation during Ordovician times in western Ireland: Scottish Journal of Geology, v. 6, p. 133–145.

Dupuy, C., and Dostal, J., 1984, Trace element geochemistry of some continental tholeiites: Earth and Planetary Science Letters, v. 67, p. 61–69.

Ferderer, R.J., 1988a, Application of Werner deconvolution to the Penokean fold-and-thrust belt, east-central Minnesota: Institute on Lake Superior Geology, 34th Annual Meeting, Marquette, Michigan, Proceedings and Abstracts, pt. 1, p. 30–32.

______ 1988b, Werner deconvolution and its application to the Penokean orogen, east-central Minnesota: Minneapolis, Minn., University of Minnesota Ph. D. dissertation, 284 p.

Goldich, S.S., and Fischer, L.B., 1986, Air-abrasion experiments in U-Pb dating of zircon: Chemical Geology, v. 58, p. 195–215.

Grout, F.F., and Wolff, J.F., Sr., 1955, The geology of the Cuyuna district, Minnesota, a progress report: Minnesota Geological Survey Bulletin 36, 144 p.

Haxby, W.F., and Turcotte, D.L., 1976, Stresses induced by the addition or removal of overburden and the associated thermal effects: Geology, v. 4, p. 181–184.

Hoffman, P.F., 1987, Early Proterozoic foredeeps, foredeep magmatism, and Superior-type iron-formations of the Canadian shield, *in* Kröner, A., ed., Proterozoic lithospheric evolution: American Geophysical Union Geodynamics Series, v. 17, p. 85–98.

_____ 1988, United plates of America, the birth of a craton—Early Proterozoic assembly and growth of Laurentia: Annual Review of Earth and Planetary Sciences, v. 16, p. 543–603.

Holm, D.K., Holst, T.B., and Ellis, M., 1988, Oblique subduction, footwall deformation, and imbrication—A model for the Penokean orogeny in east-central Minnesota: Geological Society of America Bulletin, v. 100, p. 1811–1818.

Holst, T.B., 1982, Evidence for multiple deformation during the Penokean orogeny in the Middle Precambrian Thomson Formation, Minnesota: Canadian Journal of Earth Sciences, v. 19, p. 2043–2047.

_____ 1984, Evidence for nappe development during the early Proterozoic Penokean orogeny, Minnesota: Geology, v. 12, p. 135–138.

_____ 1985, Implications of a large flattening strain for the origin of a bedding-parallel foliation in the Early Proterozoic Thomson Formation, Minnesota: Journal of Structural Geology, v. 7, p. 375–383.

Horan, M.F., Hanson, G.N., and Spencer, K.J., 1987, Pb and Nd isotope and trace element constraints on the origin of basic rocks in an early Proterozoic igneous complex, Minnesota: Precambrian Research, v. 37, p. 323–342.

Howell, D.G., Jones, D.L., and Schermer, E.R., 1985, Tectonostratigraphic terranes of the circum-Pacific region, *in* Howell, D.G., ed., Tectonostratigraphic terranes of the circum-Pacific region: Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, no. 1, p. 3–30.

Jensen, L.S., 1976, A new cation plot for classifying subalkalic volcanic rocks: Ontario Geological Survey Miscellaneous Paper 66, 22 p.

Jordan, T.E., 1981, Thrust loads and foreland basin evolution, Cretaceous, western United States: American Association of Petroleum Geologists Bulletin, v. 65, p. 2506–2520.

Keighin, C.W., Morey, G.B., and Goldich, S.S., 1972, East-central Minnesota, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota—A centennial volume: Minnesota Geological Survey, p. 240–255.

LaBerge, G.L., and Myers, P.E., 1984, Two early Proterozoic successions in central Wisconsin and their tectonic significance: Geological Society of America Bulletin, v. 95, p. 246–253.

Larue, D.K., 1981, The Chocolay Group, Lake Superior region, U.S.A.—Sedimentologic evidence for deposition in basinal and platform settings on an early Proterozoic craton: Geological Society of America Bulletin, pt. I, v. 92, p. 417–435.

_____ 1983, Early Proterozoic tectonics of the Lake Superior region—Tectonostratigraphic terranes near the purported collision zone, *in* Medaris, L.G., Jr., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 33–47.

Larue, D.K., and Ueng, W.L., 1985, Florence-Niagara terrane—An early Proterozoic accretionary complex, Lake Superior region, U.S.A.: Geological Society of America Bulletin, v. 96, p. 1179–1187.

Lucente, M.E., and Morey, G.B., 1983, Stratigraphy and sedimentology of the lower Proterozoic Virginia Formation, northern Minnesota: Minnesota Geological Survey Report of Investigations 28, 28 p.

Marsden, R.W., 1972, Cuyuna district, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota—A centennial volume: Minnesota Geological Survey, p. 227–239.

McSwiggen, P.L., 1987, Geology and geophysics of the Denham-Mahtowa area, east-central Minnesota: Minnesota Geological Survey Miscellaneous Map Series M–63, scale 1:48,000.

Morey, G.B., 1978, Lower and Middle Precambrian stratigraphic nomenclature for east-central Minnesota: Minnesota Geological Survey Report of Investigations 21, 52 p.

_____ 1983, Lower Proterozoic stratified rocks and the Penokean orogeny in east-central Minnesota, *in* Medaris, L.G., Jr., ed., Early Proterozoic geology of the Lake Superior region: Geological Society of America Memoir 160, p. 97–122.

Morey, G.B., and Morey, D.D., 1986, Distribution of iron-formations in the main Cuyuna range, east-central Minnesota: Minnesota Geological Survey Miscellaneous Map Series M–60, scale 1:48,000.

Morey, G.B., and Ojakangas, R.W., 1970, Sedimentology of the Middle Precambrian Thomson Formation, east-central Minnesota: Minnesota Geological Survey Report of Investigations 13, 32 p.

Morey, G.B., Olsen, B.M., and Southwick, D.L., 1981, Geologic map of Minnesota, east-central Minnesota, bedrock geology: Minnesota Geological Survey, scale 1:250,000.

Ojakangas, R.W., 1983, Tidal deposits in the early Proterozoic basin of the Lake Superior region—The Palms and the Pokegama Formations—Evidence for subtidal-shelf deposition of Superior-type banded iron-formation, *in* Medaris, L.G., Jr., ed., Early Proterozoic geology of the Lake Superior region: Geological Society of America Memoir 160, p. 49–66.

Pearce, J.A., and Norry, M.J., 1979, Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks: Contributions to Mineralogy and Petrology, v. 69, p. 33–47.

Pearce, T.H., Gorman, B.E., and Birkett, T.C., 1977, The relationship between major element chemistry and tectonic environment of basic and intermediate volcanic rocks: Earth and Planetary Science Letters, v. 36, p. 121–132.

Peterman, Z.E., 1966, Rb-Sr dating of middle Precambrian metasedimentary rocks of Minnesota: Geological Society of America Bulletin, v. 77, p. 1031–1044.

Peterman, Z.E., and Sims, P.K., 1988, The Goodman swell—A lithospheric flexure caused by crustal loading along the Midcontinent rift system: Tectonics, v. 7, p. 1077–1090.

Price, R.A., 1973, Large-scale gravitational flow of supracrustal rocks, southern Canadian Rockies, *in* DeJong, K.A., and Scholten, R., eds., Gravity and tectonics: New York, John Wiley, p. 491–502.

Quinlan, G.M., and Beaumont, C., 1984, Appalachian thrusting, lithospheric flexure, and Paleozoic stratigraphy of the eastern interior of North America: Canadian Journal of Earth Sciences, v. 21, p. 973–996.

Robertson, A., 1987, The transition from a passive margin to an Upper Cretaceous foreland basin related to ophiolite emplacement in the Oman Mountains: Geological Society of America Bulletin, v. 99, p. 633–653.

Schmidt, R.G., 1963, Geology and ore deposits of Cuyuna North range, Minnesota: U.S. Geological Survey Professional Paper 407, 96 p.

Schulz, K.J., 1987, Early Proterozoic evolution of a rifted continental margin in the Lake Superior region: Geological Society of America Abstracts with Programs, v. 19, p. 243.

Schwartz, G.M., 1942, Correlation and metamorphism of the Thomson Formation, Minnesota: Geological Society of America Bulletin, v. 53, p. 1001–1020.

Sedlock, R.L., and Larue, D.K., 1985, Fold axes oblique to the regional plunge and Proterozoic terrane accretion in the southern Lake Superior region: Precambrian Research, v. 30, p. 249–262.

Sims, P.K., and Peterman, Z.E., 1983, Evolution of the Penokean foldbelt, Lake Superior region, and its tectonic environment, *in* Medaris, L.G., Jr., ed., Early Proterozoic geology of the Lake Superior region: Geological Society of America Memoir 160, p. 3–14.

______ 1986, Early Proterozoic Central Plains orogen—A major buried structure in the north-central United States: Geology, v. 14, p. 488–491.

Sims, P.K., Peterman, Z.E., Klasner, J.S., Cannon, W.F., and Schulz, K.J., 1987, Nappe development and thrust faulting in the Upper Michigan segment of the Early Proterozoic Penokean orogen: Geological Society of America Abstracts with Programs, v. 19, p. 246.

Sims, P.K., Peterman, Z.E., and Schulz, K.J., 1985, The Dunbar Gneiss-granitoid dome—Implications for early Proterozoic tectonic evolution of northern Wisconsin: Geological Society of America Bulletin, v. 96, p. 1101–1112.

Sims, P.K., Van Schmus, W.R., Schulz, K.J., and Peterman, Z.E., 1989, Tectonostratigraphic evolution of the Early Proterozoic Wisconsin magmatic terranes of the Penokean orogen: Canadian Journal of Earth Sciences, v. 26, p. 2145–2158.

Southwick, D.L., 1987, Bundled slaty cleavage in laminated argillite, north-central Minnesota: Journal of Structural Geology, v. 9, p. 985–993.

Southwick, D.L., and Day, W.C., 1983, Geology and petrology of Proterozoic mafic dikes, north-central Minnesota and western Ontario: Canadian Journal of Earth Sciences, v. 20, p. 622–638.

Southwick, D.L., and Halls, H.C., 1987, Compositional characteristics of the Kenora-Kabetogama dike swarm (Early Proterozoic), Minnesota and Ontario: Canadian Journal of Earth Sciences, v. 24, p. 2197–2205.

Southwick, D.L., Meyer, G.N., and Mills, S.J., 1986, Scientific core drilling in central Minnesota—Summary of lithologic and geochemical results: Minnesota Geological Survey Information Circular 23, 186 p.

Southwick, D.L., Morey, G.B., and McSwiggen, P.L., 1988, Geologic map (scale 1:250,000) of the Penokean orogen, central and eastern Minnesota, and accompanying text: Minnesota Geological Survey Report of Investigations 37, 25 p.

Spencer, K.J., and Hanson, G.N., 1984, Pb, Nd isotope and REE constraints on east-central Minnesota Proterozoic granites—Evidence for newly derived crustal components [abs.]: Eos, v. 65, p. 292.

Sternberg, B.K., and Clay, C.S., 1977, Flambeau anomaly—A high-conductivity anomaly in the southern extension of the Canadian Shield: American Geophysical Union Monograph 20, p. 501–530.

Ueng, W.C., Fox, T.P., Larue, D.K., and Wilband, J.T., 1988, Geochemistry and petrogenesis of the early Proterozoic Hemlock volcanic rocks and the Kiernan sills, southern Lake Superior region: Canadian Journal of Earth Sciences, v. 25, p. 528–546.

Van Schmus, W.R., 1976, Early and Middle Proterozoic history of the Great Lakes area, North America: Royal Society of London Philosophical Transactions, v. 280, Series A, p. 605–628.

______ 1980, Chronology of igneous rocks associated with the Penokean orogeny in Wisconsin, *in* Morey, G.B., and Hanson, G.N., eds., Selected studies of Archean gneisses and lower Proterozoic rocks, southern Canadian Shield: Geological Society of America Special Paper 182, p. 159–168.

Van Schmus, W.R., and Bickford, M.E., 1981, Proterozoic chronology and evolution of the Midcontinent region, North America, *in* Kröner, A., ed., Precambrian plate tectonics: New York, Elsevier, p. 261–296.

Winchell, N.H., 1899, The geology of the Carlton plate, *in* Winchell, N.H., and others, Geology of Minnesota; volume 4 of the final report, 1896–1898: Minnesota Geological and Natural History Survey, p. 550–565.

Wunderman, R.L., 1988, Crustal structure across the exposed axis of the Midcontinent Rift and adjacent flanks, based on magnetotelluric data, central Minnesota-Wisconsin—A case for crustal inhomogeneity and possible reactivation tectonics: Houghton, Mich., Michigan Technological University Ph. D. dissertation, 209 p.

Wunderman, R.L., and Young, C.T., 1987, Evidence for widespread basement decollement structures and related crustal asymmetry associated with the western limb of the Midcontinent Rift: Institute on Lake Superior Geology, 33rd Annual Meeting, Wawa, Ontario, Proceedings and Abstracts, v. 33, pt. 1, p. 85–86.

Young, G.M., 1983, Tectono-sedimentary history of Early Proterozoic rocks of the northern Great Lakes region, *in* Medaris, L.G., Jr., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 15–32.

Zapffe, C., 1925, Stratigraphy and correlation of the Cuyuna iron ore district, Minnesota: Lake Superior Mining Institute Proceedings, v. 25, p. 219–227.

——— 1933, The Cuyuna iron-ore district: International Geological Congress, 16th, United States, Guidebook 27, Excursion C-4, p. 72–78.

Chapter D

The Penokean Orogeny in Minnesota and Upper Michigan—A Comparison of Structural Geology

By TIMOTHY B. HOLST

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CONTRIBUTIONS TO PRECAMBRIAN GEOLOGY OF LAKE SUPERIOR REGION

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

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The Penokean Orogeny in Minnesota and Upper Michigan—A Comparison of Structural Geology

By Timothy B. Holst[1]

Abstract

Recent geophysical studies and shallow drilling work in Minnesota have led to a reinterpretation of the Penokean orogeny. In both the Minnesota and Wisconsin-Michigan segments, north of a postulated suture zone, the orogen is interpreted to consist of an internal fold-and-thrust belt of tectonically imbricated rocks and an external (northerly) migrating foredeep. Mesoscopic and microscopic structures from rocks exposed along two transects, one in Minnesota and one in Upper Michigan, across the proposed fold-and-thrust belt/foredeep boundary have been examined, revealing a remarkable and detailed similarity between the two areas. In each region, a marked difference in geologic structure delineates the proposed boundary.

INTRODUCTION

The Precambrian craton of North America consists of a series of segments of Archean crust, which represent the remnants of microcontinents, that were assembled during Proterozoic time (Hoffman, 1988). Early Proterozoic collisional orogenies sutured the Archean microcontinents together and served to accrete juvenile Proterozoic crust to the margins of the growing protocraton (Hoffman, 1989). One of these orogenies, the Penokean orogeny, which occurred near the close of Early Proterozoic time (1,875–1,825 Ma, Van Schmus, 1976, 1980, 1981), deformed and metamorphosed rocks in Minnesota, Wisconsin, Upper Michigan, and the Superior, Southern, and Grenville provinces in Canada (for example, Holst, 1982; Maass and others, 1980; Cannon, 1973; Brocoum and Dalziel, 1974). The belt of deformed rock that constitutes the Penokean orogen is truncated on the east by the Grenville orogen and on the west by the Central Plains orogen (Sims and Peterman, 1986); it is comparable in length and width to such Phanerozoic belts as the Appalachian orogen (Southwick and others, 1988). In the Lake Superior region, the Penokean orogen is cut by younger rocks (≈1,100 Ma) of the Midcontinent rift system, a thick series of extrusive and intrusive igneous rocks and associated sedimentary rocks (fig. 1). The rocks of this rift system cut completely across the Penokean orogen and isolate the segment in Minnesota from the segment in Wisconsin and Upper Michigan (fig. 1). The geology of these two segments is similar in rough outline. Stratigraphic correlations of Early Proterozoic supracrustal rocks from the two segments are fairly well established (for example, Morey, 1973, 1978, 1983; Young, 1983; Ojakangas, 1983; Larue, 1981, 1983), and tectonic syntheses of the Penokean involving both Minnesota and Wisconsin-Michigan segments have appeared (for example, Van Schmus, 1976; Sims, 1976; Sims and others, 1980; Sims and Peterman, 1983). The purpose of this report is to point out some of the striking and detailed similarities in mesoscopic and microscopic structural geology that exist in a part of the exposed Penokean orogen in east-central Minnesota and Upper Michigan, within the context of a recent interpretation of the Penokean orogen based on geophysics and drilling in Minnesota (Southwick and Morey, this volume, ch. C).

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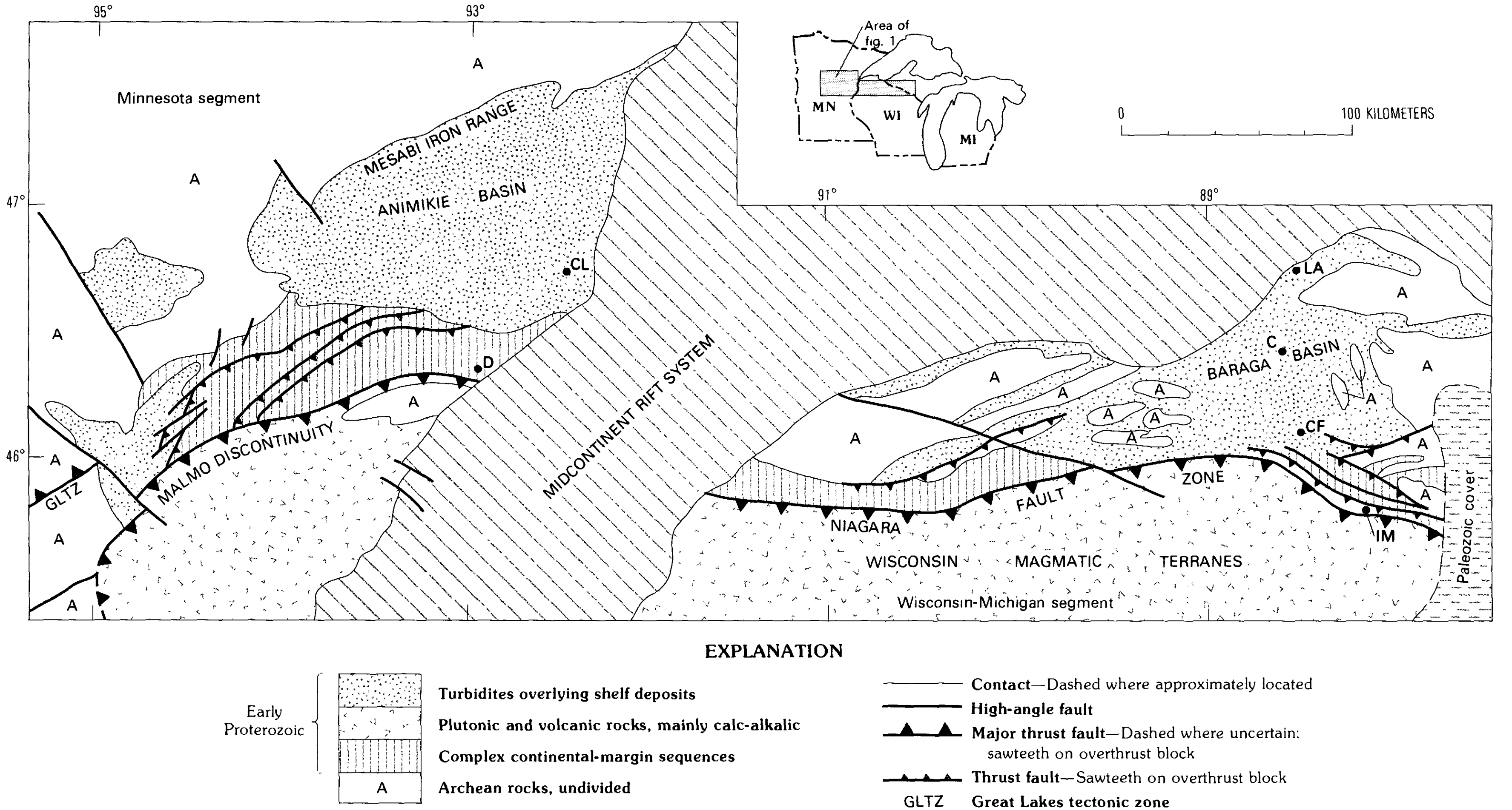

Figure 1. Minnesota and Wisconsin–Upper Michigan segments of Penokean orogen, divided by rocks of Midcontinent rift system (modified from Southwick and Morey, this volume, ch. C, fig. 1, and Sims and others, 1989). Transects along which structural geology is discussed run approximately from Cloquet, Minn. (CL) to Denham, Minn. (D), and from Covington, Mich. (C) to Iron Mountain, Mich. (IM). GLTZ, Great Lakes tectonic zone; LA, L'Anse, Mich.; CF, Crystal Falls, Mich.

to P.J. Hudleston, D.L. Southwick, and F.W. Cambray for discussions of the Penokean orogeny in Minnesota and Michigan.

GENERAL TECTONIC SETTING

Early models for the Penokean orogeny in Minnesota put forth intracratonic tectonism as a principal mechanism (Morey and Sims, 1976; Sims, 1976; Sims and others, 1980), and emphasized the role of basement rock undergoing "vertical remobilization" (Morey, 1979). In Upper Michigan as well, early discussions of the tectonic history stressed the importance of vertical movements of basement rocks in the structural evolution (Cannon, 1973). In the last decade, however, a plate collisional environment has become a principal feature of tectonic models proposed for the Penokean orogeny, both for the segment in Minnesota (Holst, 1984a, 1984b, 1984c; Morey and Southwick, 1984; Southwick and others, 1988; Southwick and Morey, this volume, ch. C) and the segment in Wisconsin and Upper Michigan (Van Schmus, 1976; Cambray, 1977, 1978; Larue, 1983; LaBerge and others, 1984; Schulz, 1983; Schulz and others, 1984; Sims and others, 1987; Klasner and Attoh, 1986; Attoh and Klasner, 1989).

East of the Midcontinent rift system the Penokean orogen consists fundamentally of two assemblages of rocks (Cannon, 1973; Sims and Peterman, 1983; Larue, 1983). The northern assemblage consists of Early Proterozoic turbidites and underlying shelf deposits of the Marquette Range Supergroup (Cannon and Gair, 1970), which overlie Archean basement and are exposed around and between basement highs (fig. 1). These rocks are thought to be broadly correlative to the Early Proterozoic supracrustal rocks of the Mille Lacs and Animikie Groups in Minnesota (Cannon, 1973; Larue, 1981, 1983; Morey, 1983; Ojakangas, 1983; Sims and Peterman, 1983). The southern assemblage is composed primarily of plutonic and volcanic rocks of the Wisconsin magmatic terranes. Geochemical studies have shown these rocks to be of island arc affinity (Schulz, 1983; Greenberg and Brown, 1983; Schulz and others, 1984; Sims and others, 1989). The boundary between these two assemblages is the Niagara fault zone. A number of tectonic models identifying plate collision (some, multiple collisions) in this area cite the Niagara fault zone as the collision boundary or suture zone (Van Schmus, 1976; Cambray, 1977, 1978; Larue, 1983; LaBerge and others, 1984; Sims and others, 1985; Klasner and Attoh, 1986; Klasner, Ojakangas, and others, 1988; Klasner, Sims, and others, 1988; Attoh and Klasner, 1989).

West of the Midcontinent rift system, surface exposure of the Penokean orogen is quite poor, but recent geophysical work and shallow drilling have led to a much clearer picture (Southwick and others, 1988; Southwick and Morey, this volume, ch. C). Southwick and Morey have interpreted this segment of the orogen to consist of an internal fold-and-thrust belt and an external turbidite basin (the Animikie basin and its outliers, fig. 1) developed during a collisional event entailing southward-dipping subduction. Several structural terranes, each with its own stratigraphy, structural style, and metamorphic character, make up the internal fold-and-thrust belt. Southwick and Morey (this volume, ch. C) have presented tectonic and petrogenetic interpretations for each of the terranes, and suggested that the boundary between two of the terranes, the Malmo discontinuity (fig. 1), may be correlative with the Niagara fault zone across the Midcontinent rift. The turbidite basin (the Animikie and outliers), external to the fold-and-thrust belt, is interpreted as a migrating foredeep (Hoffman, 1987), or more likely, a series of foredeeps (Southwick and Morey, this volume, ch. C), whose sediments became involved in the deformation at the margin of the fold-and-thrust belt.

Southwick and Morey (this volume, ch. C) pointed out the broad similarities between rocks east of the Midcontinent rift just north of the Niagara fault zone and the fold-and-thrust belt in Minnesota, and the similarities in stratigraphy, sedimentology, and structural style between the Animikie Group in the Animikie basin in Minnesota and the rocks of the Early Proterozoic Baraga Group in the Baraga basin (fig. 1) in Upper Michigan; they have suggested that these similarities fit a foredeep model.

COMPARISON OF STRUCTURAL GEOLOGY

Limited rock exposures exist on a roughly north-south transect across parts of the postulated internal fold-and-thrust belt, and on one across the postulated external foredeep basins in both Minnesota and Upper Michigan. (Approximate locations of the transects are shown by letter symbols, fig. 1.) Exposures in Minnesota extend from Cloquet on the north roughly to Denham on the south, and are in rocks historically mapped as Early Proterozoic Denham and Thomson Formations; structure along the Minnesota transect, described in detail elsewhere (for example, Holst, 1982, 1984c, 1985a; Holm, 1986a), is summarized herein. In Michigan, the exposures extend from Covington on the north to just north of Iron Mountain on the south, and are in rocks that are mapped as Michigamme Formation (Cannon, 1986). Mesoscopic and microscopic structures in rocks along these two transects suggest the existence in each area of two fundamentally different structural terranes, a northern and a southern terrane.

Descriptive Structural Geology in Minnesota Terranes

Exposures of Early Proterozoic metasedimentary and metavolcanic rocks historically called the Thomson Formation consist of a thick sequence of interbedded slate, slaty graywacke and metagraywacke, and some intercalated volcanic rocks. Some of the southern exposures previously mapped as Thomson Formation have recently been assigned to other, as yet unnamed units of Early Proterozoic supracrustal rocks, which are older than the type locality of the Thomson Formation (Southwick and Morey, 1988; Southwick and others, 1988; Southwick and Morey, this volume, ch. C). The southern two-thirds of the region of Early Proterozoic supracrustal rocks, here designated the Minnesota southern structural terrane, has a pervasive, nearly bedding-parallel foliation (S_1). It ranges from a slaty cleavage in the north to a schistosity in the south (Holst, 1982). Strain analysis (Holst, 1985a) has firmly established the tectonic nature of this bedding-parallel foliation. Also present in the southern structural terrane are isoclinal recumbent folds with east-west fold axes (F_1), whose scales range from centimeters to kilometers (nappes). The main foliation in the southern terrane is axial-planar to these recumbent folds and is nearly always subparallel to bedding, as the folds are isoclinal and hinge regions are relatively rare.

Both the northern and southern structural terranes in Minnesota have been affected by later gentle to open (locally closed) upright folds. Fold axial surfaces strike east-west and dip vertically or steeply to the south (northward vergence). Fold axes have horizontal to gentle plunges either east or west, except where folds die out rapidly along strike, where axes may plunge up to 60°. In the southern structural terrane, these upright folds (F_2) refold the earlier isoclinal recumbent folds (F_1). In the northern terrane no folding took place prior to the upright generation of folds.

A well-developed cleavage, vertical or dipping steeply to the south (axial-planar to the upright folds), is present in both the northern and southern structural terranes. In the northern structural terrane this cleavage is well developed, continuous, and slaty in the finer grained units. In the units with graded bedding, and in the units with interlaminated fine and coarse layers, the continuous cleavage grades into a disjunctive spaced cleavage (terminology of Powell, 1979). The spacing of the cleavage domains ranges from continuous up to 1 cm in some of the coarser grained units, but it is rarely more than a few millimeters. Cleavage domains constitute from 25 percent of the rock (in the thick graywacke units) to 100 percent (in the slates with a continuous cleavage). Domain shapes range from rough to smooth (smooth shapes predominate) with some anastomosing shapes. Within the microlithons, a weak fabric, at least, is developed everywhere; and commonly the fabric is strong to complete (terminology of Powell, 1979). In the southern structural terrane, the steep foliation is a well-developed crenulation cleavage (S_2). This S_2 cleavage can be discrete but is most commonly transitional to zonal, or entirely zonal (Gray, 1977; Powell, 1979). Spacing of the cleavage domains is variable. For the most part the spaced crenulation cleavage strikes east-west and dips steeply to the south or is vertical, and is axial-planar to the F_2 folds. Around some microfolds, however, the spaced crenulation cleavage may fan, or be at a constant angle (up to 40°) to the axial plane on one limb, and axial-planar on the other limb. The intersection of S_1 and S_2 defines a well-developed lineation in the rock, trending east-west with subhorizontal plunges; a mineral lineation of the same orientation exists as well.

Underlying the southern part of what has historically been called the Thomson Formation is the Early Proterozoic Denham Formation. The Denham has now been divided into lower and upper parts by Southwick and others (1988). The lower member comprises quartzite, micaceous quartzite, and pelitic schist, with some local conglomerate and mafic to intermediate metavolcanic rocks. The upper member is dominantly quartzite, with interbedded dolomite marble (Southwick and others, 1988). The rocks of this formation have been multiply deformed and metamorphosed in a fashion similar to the overlying rocks (Holm, 1986a, 1986b) and are part of the same nappe terrane. The Denham Formation is a sequence of primarily quartz rich metasedimentary rocks (meta-arkose, quartzite, mica schist, and garnet-staurolite schist) with minor amounts of marble and volcanic rocks. Bedding strikes east-west and dips steeply. A nearly bedding-parallel foliation is present everywhere in the Denham Formation. The foliation is refracted at a higher angle to bedding in the more competent arkosic and quartzitic units. The foliation and bedding have been folded with the development, locally, of a crenulation cleavage. Orientations of axial surfaces to these folds vary from horizontal to vertical and strike east-west. The Denham Formation also contains a very well developed, nearly horizontal, east-west mineral (extension) lineation and crenulation lineation. Chocolate-tablet boudinage of quartz veins occurs parallel to bedding throughout the area.

In the Minnesota northern structural terrane, some late-stage features deform the steep cleavage in the Thomson Formation. Kink bands are locally well developed, and although their orientation is quite variable, poles to more than 100 kink bands define a single maximum on an equal-area projection (Clark, 1985), with a gentle dip to the north. The gentle dip of the kink bands indicates a subvertical finite compression during their formation, estimated to be about 5 percent by Clark (1985). In addition, along a few isolated outcrops in the northern terrane, the cleavage dips very gently (Clark, 1985). No younger cleavage is developed, and the rocks appear identical, both mesoscopically and microscopically, to rocks of the surrounding area, except that the cleavage is flat, not subvertical as it is in virtually the entire northern terrane. The areas of exposure of this amomalously oriented cleavage are small, few, and isolated from other exposures by thick glacial cover.

In summary, the essential features of the northern structural terrane are a single generation of upright folds, with an axial-planar cleavage, and some later features such as kink bands and isolated areas of flat cleavage. The essential features of the southern structural terrane are an early generation of isoclinal recumbent folds with an axial-planar cleavage (subparallel to bedding in all but rare hinge regions of the early folds), and a later set of upright folds with associated axial-planar crenulation cleavage. The rocks of the southern terrane also show a well-developed lineation in most areas. Detailed mapping has allowed a boundary to be drawn between the area of a single main Penokean deformation in the north (the northern structural terrane), and the area of two Penokean deformations in the south (the southern structural terrane). This boundary was interpreted by Holst (1984c) as a nappe front because of the abrupt nature of the change across this terrane boundary, and because the refraction pattern in the early foliation just south of this boundary suggests that a nappe front must be located in the immediate vicinity to the north. This structural boundary lies near the boundary between the internal fold-and-thrust belt and the external turbidite basin (foredeep), postulated by Southwick and Morey (this volume, ch. C). Some rocks at the south margin of the younger, external foredeep are part of the southern structural terrane (Southwick and others, 1988; Southwick and Morey, this volume, ch. C, fig. 2). For the most part, however, the rocks of the inferred foredeep are part of the northern structural terrane, and were folded only when the underlying rocks of the southern structural terrane were refolded. Also, within the northern terrane, the effects of deformation die out to the north, so that the rocks on the north margin of the basin (in particular, the Mesabi iron range) show little effect of the Penokean orogeny.

Strain Analysis in Minnesota Terranes

Finite strain markers, in the form of deformed concretions, mud chips, and conglomerate clasts, have provided data for the determination of finite strain at 23 localities in the Penokean orogen in Minnesota (Holst, 1985a), 13 in the northern structural terrane, and 10 in the southern structural terrane. Details of the analysis are omitted here, but may be found in Holst (1985a). The strain analysis emphasizes the difference in structural history of the two structural terranes (fig. 2). The northern terrane shows strains typical of slate belts (Wood, 1974) with all data points plotting within the flattening field. Strains in the rocks of the southern terrane reveal a different geometry, reflecting the more complex structural history. In the analytical model, Holst (1985a) removed the strains associated with the second deformation (northern terrane strain) from the total strain in the rocks of the southern terrane in an attempt to infer the strain associated with the early, nappe-producing deformation (fig. 2). Further deformation inversion modeling by Holm and others (1988), taking into account possible volume loss and rotational effects, confirms that the strain associated with the early deformation produced a large vertical finite shortening (in the range −84 percent to −89 percent) with horizontal extensions of greater than 200 percent in both orogen-parallel and orogen-perpendicular directions. Holst (1985b) used strain estimates for the early deformation in the southern terrane to produce models of this deformation factored into simple shear and pure shear components, or simple shear and constant-volume non-pure shear components. The results of that modeling showed that shear indeed played a large role in the development of the strain during nappe emplacement as suggested in other studies of strain within nappes (for example, Ramsay and others, 1983; Siddans, 1983; Coward and Kim, 1981).

Comparative Structural Geology in Minnesota and Michigan

In Michigan, in the area from Covington (fig. 1) south to the Baraga County–Iron County line (a distance of about 15 km), appear rocks and structures similar to the northern terrane in Minnesota. The rocks comprise slate, slaty graywacke, and metagraywacke, identical in outcrop appearance to the type area of the Thomson Formation in Minnesota. A single foliation exists, again a continuous slaty cleavage in the fine-grained units and a disjunctive

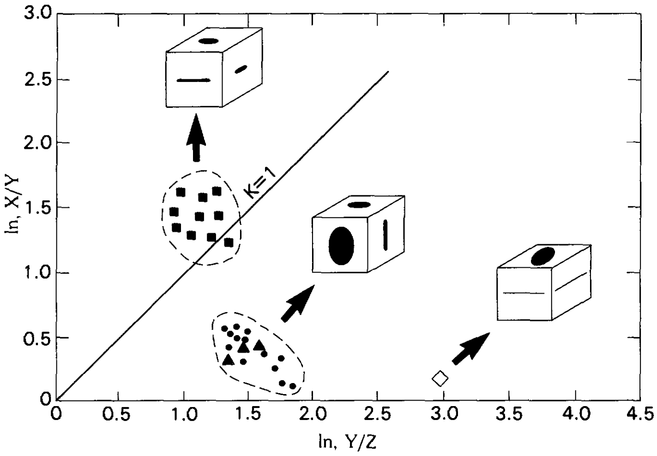

Figure 2. Logarithmic deformation plot showing results of three-dimensional strain determinations in the Penokean orogen in Minnesota and Upper Michigan (modified from Holst, 1985a, figs. 6, 8). K=1 is line of plane strain at no volume loss. Solid boxes, plotting just into the prolate field for the most part, are data from Minnesota southern structural terrane. Plotting in the flattening field are data from Minnesota northern structural terrane (solid dots) and from Upper Michigan northern structural terrane (solid triangles). Open diamond is inferred strain of the first, nappe-producing deformation in Minnesota southern terrane (see Holst, 1985a, for details). Three cubes are sketched to illustrate the strain ellipsoid represented by the group of data in each case. For each cube, the top face is horizontal, and the front face is an east-west section, with east on the right. The difference in finite strain in northern and southern terranes is clear, and reflects a difference in deformation history.

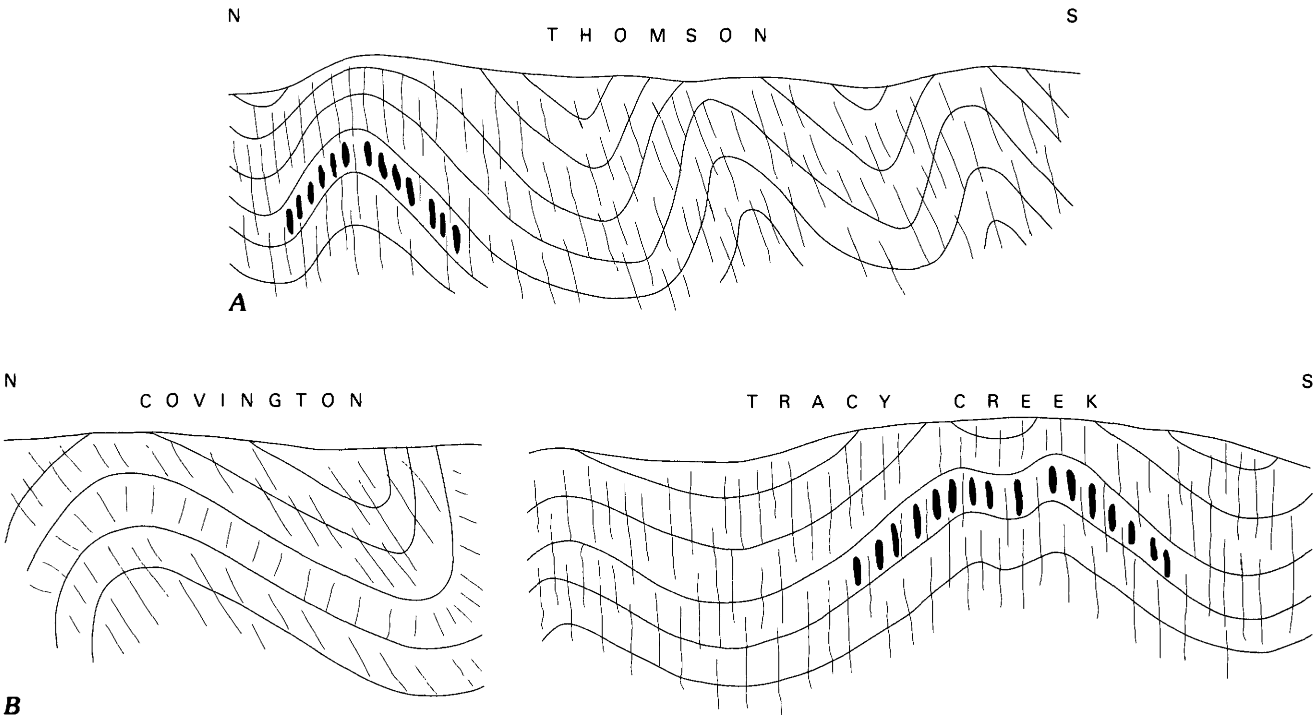

Figure 3. Sketches comparing the mesoscopic structures in the northern structural terranes in *A*, Minnesota, and *B*, Upper Michigan. Length of each section about 70 m. *A*, Section in Minnesota near type area at Thomson. *B*, Covington is at north end of transect in Upper Michigan shown in figure 1, and Tracy Creek is about 12 km south of Covington. Shown schematically are upright to north-verging folds, axial-planar cleavage, and some of the deformed concretions amenable to strain analysis.

space cleavage in the coarse-grained graywacke beds. In thin section, rocks from Minnesota and Michigan appear essentially identical. The attitude of the cleavage changes somewhat from north to south along this part of the transect, dipping as gently as 40°–50° to the south at Covington, and dipping nearly vertically 15 km to the south. The cleavage is axial-planar to some mesoscopic folds, and normal bedding-cleavage vergence relationships (between slate and graywacke beds) are observed. The folds are upright in the southern part of the transect, but axial surfaces dip as gently as 40°–50° south at Covington, showing northward vergence. Where fold axes can be found, they are subhorizontal, and bedding-cleavage intersections along the transect are subhorizontal. Late-stage kink bands also exist here, and are also gently dipping. In outcrop and in thin section the kink bands in Minnesota and Upper Michigan show detailed similarity. Holst and R.G. Clark have detailed work in progress concerning these kinks.

Deformed concretions and mud chips, whose appearance is again similar even in detail to strain markers in Minnesota, exist in the rocks along this part of the transect in Upper Michigan. Strain analysis of rocks in this area is at a preliminary stage, but three-dimensional strain determinations have been completed for three outcrops located 2–15 km south of Covington. Results reveal flattening strains similar to those in the Minnesota northern terrane (fig. 2), which are in marked contrast to the Minnesota southern terrane. Similarities between the structural features found in the northern structural terranes in Minnesota and Michigan are shown in figure 3.

In the southern part of the transect in Upper Michigan, rocks were examined at Horse Race Rapids just south of Crystal Falls and just north of Iron Mountain—at Steele Farm and along the Sturgeon River. The structural geology of these rocks is distinctly different from that of the rocks of the northern terrane in Michigan, in the area just south of Covington, and quite similar to the structural geology of rocks in the Minnesota southern terrane. A ubiquitous feature of the rocks in this area is a well-developed foliation that is subparallel to bedding, and the rocks are commonly lineated. In this southern terrane in Michigan, two phases of folding are also evident. The early phase is isoclinal and recumbent, and a well-developed foliation is axial-planar to the folds (the ubiquitous foliation mentioned above). F_1 fold hinges are quite rare, so this foliation is usually found to be subparallel to bedding. F_2 folds (fig. 4) are open, upright, and subhorizontal. A spaced crenulation cleavage is found in some places, in an attitude which is axial-planar to the F_2 folds. A lineation is parallel to the intersection of the two foliations. Figure 5 shows that small-scale refolded F_1 folds and associated foliations from the southern structural terranes in Minnesota and Upper Michigan are remarkably similar. Although no strain markers have yet been identified in the southern structural terrane in Upper Michigan, the similarity of style and geometry of folds and foliations to the Minnesota southern structural terrane suggests that these areas have similar strain histories, each considerably different from the known strains in the northern terranes.

DISCUSSION

The presence of nappes and (or) thrust faults has recently been reported in the Penokean orogen in Upper Michigan (for example, Sims and others, 1987; Klasner, Ojakangas, and others, 1988; Maharidge, 1986; Stahl and Matty, 1988). In the area near L'Anse (fig. 1), W.J. Gregg and students have mapped an east-west-trending thrust, named the L'Anse thrust, which is not specifically exposed but which is inferred, based on the differences in structural style and lithology seen in exposures on the shores of Keweenaw Bay of Lake Superior, and those just inland on the Falls River (Sikkala and Gregg, 1987; Klasner, Sims, and others, 1988). The exposures on Keweenaw Bay show a single phase of folding and a single cleavage (fig. 6). Along the Falls River, early fold axial surfaces dip moderately to the south for the most part; but in places they are nearly horizontal, and in these areas there is a steep crenulation cleavage. The crenulation cleavage has been interpreted (Sikkala and Gregg, 1987) as large kink-like younger folds (fig. 6). The areas of anomalously flat cleavage in the northern structural terrane in Minnesota may well reflect a later kink-like folding, similar to that seen at Falls River, Mich. In Minnesota, however, no second cleavage has developed. A number of other thrust faults have been interpreted in a transect across the orogen to the south of L'Anse (Klasner, Sims, and others, 1988). Most of these are also inferred to exist between outcrops because of structural and (or) lithologic differences.

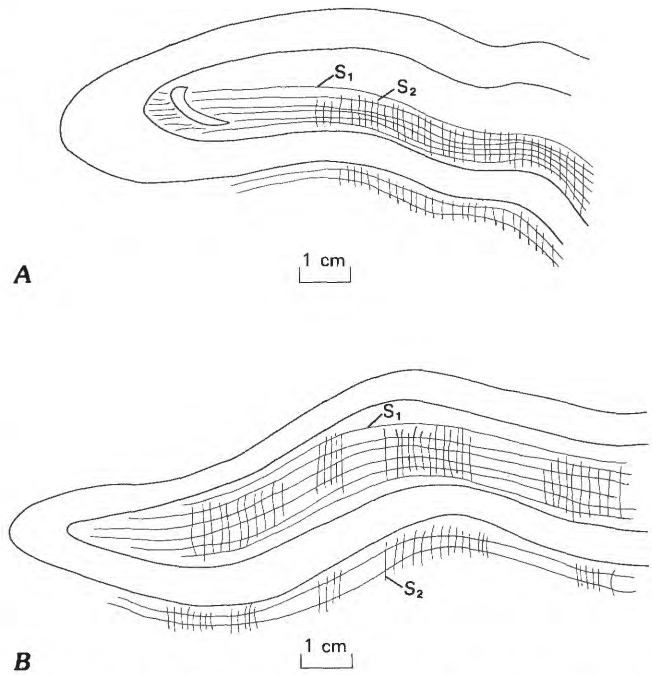

Figure 5. Small-scale refolded F_1 folds and associated foliations from outcrops in the southern structural terrane in *A*, Minnesota, and *B*, Upper Michigan. The folds are defined in each case by metagraywacke embedded in slate or schist matrix. S_1 is axial-planar to the early fold, and S_2 (vertical in sketch) is axial-planar to F_2 folds. Each fold exhibits Ramsay type 3 interference pattern (Ramsay, 1967), and geometries and attitudes of folds and axial-planar foliations are nearly identical in Minnesota and Michigan. Outcrop in Minnesota (*A*) is near Park Lake, between Cloquet and Denham along the traverse shown in figure 1. Outcrop in Michigan (*B*), same as in figure 4.

Figure 4. F_2 folds in hand sample from outcrop of Michigamme Formation along the Sturgeon River just north of Iron Mountain, Mich. (alternate stop 13 of Klasner, Sims, and others, 1988). Coin (1.9 cm diameter) sits on top of the hand sample on an undulating S_1 surface. F_2 folds with axial-planar S_2 crenulation cleavage are observable on front face of the sample. Lineation seen on the top surface is the intersection of the S_2 crenulation cleavage and the S_1 foliation.

North-verging folds, some of them with axial surfaces of low to moderate dip, certainly do exist in the northern terrane in Upper Michigan, and north-verging folds also exist in the Minnesota northern terrane. Although the best evidence for nappe-scale folding and overthrust tectonic style in Minnesota is in the southern structural terrane (Holst, 1984c, 1985b), with much of the best evidence for such features being exposed near the boundary between the northern and southern terranes, detachment thrusting may well exist at depth in the northern terrane in Minnesota, to

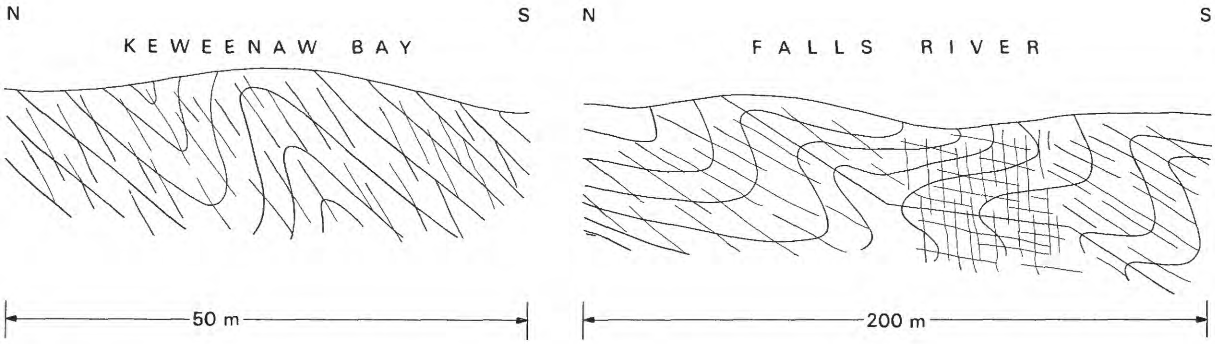

Figure 6. Sketch cross sections (modified from Sikkala and Gregg, 1987; W.J. Gregg, oral commun., 1989) from Keweenaw Bay and Falls River exposures near L'Anse in Upper Michigan (location, fig. 1). Falls River section approximately 200 m long; Keweenaw Bay section about 50 m long. These two sections are on opposite sides of proposed L'Anse thrust (Sikkala and Gregg, 1987; Klasner, Sims, and others, 1988). North-verging folds are similar to those in Minnesota northern structural terrane; younger, kink-like fold at the Falls River section may be represented in Minnesota by isolated exposures where cleavage is nearly horizontal. Crest line of fold shown by solid line.

accommodate the shortening associated with the upright folds. Indeed the argument can be (and has been) made that detachment must lie at some level within all fold belts. Detachment thrusting may well also exist in the northern terrane in Michigan, but the structural geology indicates that the deformation history in the northern terrane is fundamentally different from that of the southern terrane.

Analysis of mesoscopic and microscopic structural geology in both Minnesota and Michigan corroborates the suggestion by Southwick and Morey (this volume, ch. C) that the Penokean orogen consists of an internal fold-and-thrust belt with tectonically imbricated sequences of supracrustal rocks, and a relatively complex deformation history, and a northern external turbidite basin (foredeep) with a simpler deformation history.

REFERENCES CITED

Attoh, K., and Klasner, J.S., 1989, Tectonic implications of metamorphism and gravity field in the Penokean orogen of northern Michigan: Tectonics, v. 8, p. 911–933.

Brocoum, S.J., and Dalziel, I.W.D., 1974, The Sudbury Basin, the southern province, the Grenville Front, and the Penokean orogeny: Geological Society of America Bulletin, v. 85, p. 1571–1580.

Cambray, F.W., 1977, Field guide to the Marquette district, Michigan: Michigan Basin Geological Society Annual Meeting, 62 p.

——— 1978, Plate tectonics as a model for the environment of deposition and deformation of the Early Proterozoic (Precambrian X) of northern Michigan: Geological Society of America Abstracts with Programs, v. 10, p. 376.

Cannon, W.F., 1973, The Penokean orogeny in northern Michigan, *in* Young, G.M., ed., Huronian stratigraphy and sedimentation: Geological Association of Canada Special Paper 12, p. 211–249.

——— 1986, Bedrock geologic map of the Iron River 1°×2° quadrangle, Michigan and Wisconsin: U.S. Geological Survey Miscellaneous Investigations Map I–1360–B, scale 1:250,000.

Cannon, W.F., and Gair, J.E., 1970, A revision of stratigraphic nomenclature for middle Precambrian rocks in northern Michigan: Geological Society of America Bulletin, v. 81, p. 2843–2846.

Clark, R.G., 1985, The structural geology of the Thomson Formation; Cloquet and Esko quadrangles, east-central Minnesota: Duluth, Minn., University of Minnesota Duluth M.S. thesis, 114 p.

Coward, M.P., and Kim, J.H., 1981, Strain within thrust sheets, *in* McKlay, K.R., and Price, N.J., eds., Thrust and nappe tectonics: Geological Society of London Special Publication 9, p. 275–292.

Gray, D.R., 1977, Morphologic classification of crenulation cleavages: Journal of Geology, v. 85, p. 229–235.

Greenberg, J.K., and Brown, B.A., 1983, Lower Proterozoic volcanic rocks and their setting in the southern Lake Superior district, *in* Medaris, L.G., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 67–84.

Hoffman, P.F., 1987, Early Proterozoic foredeeps, foredeep magmatism, and Superior-type iron formations of the Canadian Shield, *in* Kroner, A., ed., Proterozoic lithosphere evolution: American Geophysical Union Geodynamics Series, v. 17, p. 85–98.

——— 1988, United plates of America, the birth of a craton—Early Proterozoic assembly and growth of Laurentia: Annual Reviews of Earth and Planetary Sciences, v. 16, p. 543–603.

——— 1989, Speculations on Laurentia's first gigayear (2.0 to 1.0 Ga): Geology, v. 17, p. 135–138.

Holm, D.K., 1986a, A structural investigation and tectonic interpretation of the Penokean orogeny—East-central Minnesota: Duluth, Minn., University of Minnesota Duluth M.S. thesis, 114 p.

——— 1986b, An account of multiphase deformation during the Penokean orogeny—Evidence from analysis of the Archean McGrath Gneiss and overlying Early Proterozoic metasedimentary rocks in east-central Minnesota: 32nd Annual Institute on Lake Superior Geology, Wisconsin Rapids, Wisconsin, Abstracts, v. 32, p. 32–33.

Holm, D.K., Holst, T.B., and Ellis, M., 1988, Oblique subduction, footwall deformation, and imbrication—A model for the Penokean orogeny in east-central Minnesota: Geological Society of America Bulletin, v. 100, p. 1811–1818.

Holst, T.B., 1982, Evidence for multiple deformation during the Penokean orogeny in the Middle Precambrian Thomson Formation, Minnesota: Canadian Journal of Earth Sciences, v. 19, p. 2043–2047.

______ 1984a, Penokean tectonics—Constraints from the structural geology in east-central Minnesota: 30th Annual Institute on Lake Superior Geology, Wausau, Wisconsin, Abstracts, v. 30, p. 19.

______ 1984b, The Early Proterozoic Penokean orogeny as a convergent plate boundary: Geological Association of Canada Program with Abstracts, v. 9, p. 75.

______ 1984c, Evidence for nappe development during the early Proterozoic Penokean orogeny, Minnesota: Geology, v. 12, p. 135–138.

______ 1985a, Implications of a large flattening strain for origin of a bedding-parallel foliation in the Early Proterozoic Thomson Formation, Minnesota: Journal of Structural Geology, v. 7, p. 375–383.

______ 1985b, Strain within early Proterozoic nappes in the Penokean orogenic belt, Minnesota: Geological Society of America Abstracts with Programs, v. 17, p. 293.

Klasner, J.S., and Attoh, K., 1986, Tectonic implications from metamorphic and gravity data at the Peavy and Republic nodes, northern Michigan: Geological Society of America Abstracts with Programs, v. 18, p. 658.

Klasner, J.S., Ojakangas, R.W., Schulz, K.J., and LaBerge, G.L., 1988, Evidence for development of an early Proterozoic overthrust-nappe system in the Penokean Orogen of northern Michigan: 34th Annual Institute on Lake Superior Geology, Marquette, Michigan, Abstracts and Proceedings, v. 34, p. 56–57.

Klasner, J.S., Sims, P.K., Gregg, W.J., and Gallup, C., 1988, A structural traverse across a part of the Penokean orogen illustrating early Proterozoic overthrusting in northern Michigan: 34th Annual Institute on Lake Superior Geology, Marquette, Michigan, Field Trip Guidebooks, v. 34, pt. 2, p. C1–C36.

LaBerge, G.L., Schulz, K.J., and Myers, P.E., 1984, The plate tectonic history of north-central Wisconsin: 30th Annual Institute on Lake Superior Geology, Wausau, Wisconsin, Abstracts, v. 30, p. 25–27.

Larue, D.K., 1981, The Chocolay Group, Lake Superior region, U.S.A.—Sedimentologic evidence for deposition in basinal and platform settings on an early Proterozoic craton: Geological Society of America Bulletin, v. 92, pt. 1, p. 417–435.

______ 1983, Early Proterozoic tectonics of the Lake Superior region—Tectonostratigraphic terranes near the purported collision zone, *in* Medaris, L.G., Jr., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 33–47.

Maass, R.S., Medaris, L.G., Jr., and Van Schmus, W.R., 1980, Penokean deformation in central Wisconsin, *in* Morey, G.B., and Hanson, G.N., Selected studies of Archean gneisses and lower Proterozoic rocks, southern Canadian Shield: Geological Society of America Special Paper 182, p. 147–157.

Maharidge, A.D., 1986, The structural and tectonic history of a portion of the Felch Trough, central Dickinson County, Michigan: Bowling Green, Ohio, Bowling Green State University M.S. thesis, 67 p.

Morey, G.B., 1973, Stratigraphic framework of middle Precambrian rocks in Minnesota, *in* Young, G.M., ed., Huronian stratigraphy and sedimentation: Geological Association of Canada Special Paper, v. 12, p. 211–249.

______ 1978, Lower and Middle Precambrian stratigraphic nomenclature for east-central Minnesota: Minnesota Geological Survey Report of Investigations 21, 52 p.

______ 1979, Field trip guidebook for the Precambrian geology of east-central Minnesota: Minnesota Geological Survey, Guidebook Series 12, 28 p.

______ 1983, Lower Proterozoic stratified rocks and the Penokean orogeny in east-central Minnesota, *in* Medaris, L.G., Jr., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 97–112.

Morey, G.B., and Sims, P.K., 1976, Boundary between two Precambrian W terranes in Minnesota and its geologic significance: Geological Society of America Bulletin, v. 87, p. 141–152.

Morey, G.B., and Southwick, D.K., 1984, Early Proterozoic geology of east-central Minnesota—A review and reappraisal: 30th Annual Institute on Lake Superior Geology, Wausau, Wisconsin, Abstracts, v. 30, p. 35–36.

Ojakangas, R.W., 1983, Tidal deposits in the Early Proterozoic basin in the Lake Superior region—The Palms and Pokegama Formations—Evidence for subtidal-shelf deposition of Superior-type banded iron formations, *in* Medaris, L.G., Jr., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 49–66.

Powell, C. McA., 1979, A morphological classification of rock cleavage: Tectonophysics, v. 58, p. 21–34.

Ramsay, J.G., 1967, Folding and fracturing of rocks: New York, McGraw Hill, 568 p.

Ramsay, J.G., Casey, M., and Kligfield, R., 1983, Role of shear in development of the Helvetic fold-thrust belt of Switzerland: Geology, v. 11, p. 439–442.

Schulz, K.J., 1983, Geochemistry of the volcanic rocks of northeastern Wisconsin: 29th Annual Institute on Lake Superior Geology, Houghton, Michigan, Abstracts and Proceedings, v. 29, p. 39.

Schulz, K.J., LaBerge, G.L., Sims, P.K., Peterman, Z.E., and Klasner, J.S., 1984, The volcanic-plutonic terrane of northern Wisconsin—Implications for early Proterozoic tectonism, Lake Superior region: Geological Association of Canada Program with Abstracts, v. 9, p. 103.

Siddans, A.W.B., 1983, Finite strain patterns in some Alpine nappes: Journal of Structural Geology, v. 5, p. 441–448.

Sikkala, K.M., and Gregg, W.J., 1987, A structural analysis of Proterozoic metasediments, northern Falls River, Baraga County, Michigan: 33rd Annual Institute on Lake Superior Geology, Wawa, Ontario, Abstracts and Proceedings, v. 33, p. 65–66.

Sims, P.K., 1976, Precambrian tectonics and mineral deposits, Lake Superior region: Economic Geology, v. 71, p. 1092–1118.

Sims, P.K., Card, K.D., Morey, G.B., and Peterman, Z.E., 1980, The Great Lakes tectonic zone—A major crustal structure in central North America: Geological Society of America Bulletin, v. 91, pt. 1, p. 690–698.

Sims, P.K., and Peterman, Z.E., 1983, Evolution of Penokean foldbelt, Lake Superior region, and its tectonic environment, *in* Medaris, L.G., Jr., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 3–14.

______ 1986, Early Proterozoic Central Plains orogen—A major buried structure in the north-central United States: Geology, v. 14, p. 488–491.

Sims, P.K., Peterman, Z.E., Klasner, J.S., Cannon, W.F., and Schulz, K.J., 1987, Nappe development and thrust faulting in the Upper Michigan segment of the early Proterozoic Penokean orogen: Geological Society of America Abstracts with Programs, v. 19, p. 246.

Sims, P.K., Peterman, Z.E., and Schulz, K.J., 1985, The Dunbar Gneiss–granitoid dome—Implications for early Proterozoic tectonic evolution of northern Wisconsin: Geological Society of America Bulletin, v. 96, p. 1101–1112.

Sims, P.K., Van Schmus, W.R., Schulz, K.J., and Peterman, Z.E., 1989, Tectonostratigraphic evolution of the early Proterozoic Wisconsin magmatic terranes of the Penokean orogen: Canadian Journal of Earth Sciences, v. 26, p. 2145–2158.

Southwick, D.L., and Morey, G.B., 1988, Tectonic imbrication and foredeep development in the Penokean orogen, east-central Minnesota: 34th Annual Institute on Lake Superior Geology, Marquette, Michigan, Abstracts and Proceedings, v. 34, p. 106–107.

Southwick, D.L., Morey, G.B., and McSwiggen, P.L., 1988, Geologic map (scale 1:250,000) of the Penokean orogen, central and eastern Minnesota, and accompanying text: Minnesota Geological Survey Report of Investigations 37, Saint Paul, Minnesota, 25 p.

Stahl, S.D., and Matty, D.J., 1988, Early Penokean deformation in the Peavy Pond area, northern Michigan—Evidence from the Michigamme Formation and the Peavy Pond Igneous Complex: 34th Annual Institute on Lake Superior Geology, Marquette, Michigan, Abstracts and Proceedings, v. 34, p. 108–109.

Van Schmus, W.R., 1976, Early and Middle Proterozoic history of the Great Lakes area, North America: Philosophical Transactions of the Royal Society of London, v. 280, p. 605–628.

______ 1980, Chronology of igneous rocks associated with the Penokean orogeny in Wisconsin: Geological Society of America Special Paper 182, p. 159–168.

______ 1981, Possible interpretations of the Penokean orogeny: International Proterozoic Symposium, University of Wisconsin, Madison, Abstracts Volume, p. 44.

Wood, D.S., 1974, Current views of the development of slaty cleavage: Annual Reviews of Earth and Planetary Science Letters, v. 2, p. 1–35.

Young, G.M., 1983, Tectono-sedimentary history of early Proterozoic rocks of the northern Great Lakes region, *in* Medaris, L.G., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 15–32.

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