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# GEOLOGIC MAP (SCALE 1:250,000) OF THE PENOKEAN OROGEN, CENTRAL AND EASTERN MINNESOTA, AND ACCOMPANYING TEXT

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ILLUSTRATIONS

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**By**

**D.L. Southwick, G.B. Morey, and Peter L. McSwiggen**

**ABSTRACT**

The geology of the Animikie basin and contiguous rocks of Early Proterozoic age in central and eastern Minnesota (collectively constituting the western end of the Penokean orogen) is reinterpreted in terms of plate-tectonic theory on the basis of new geophysical and geological data. Fundamentally the Penokean orogen is inferred to consist of a deformed foreland basin or tectonic foredeep, encompassing the main bowl of the Animikie basin together with the newly recognized Long Prairie basin and Nimrod outlier, and a structurally and stratigraphically complex fold-and-thrust belt, encompassing the Cuyuna district, the Glen Township area, and adjacent areas to the south and east. The fold-and-thrust belt contains tectonically dismembered and reassembled sequences of volcanic and sedimentary rocks that are difficult to correlate with assurance from one structural panel to another. These greatly deformed rocks are unconformably overlain by less deformed sedimentary strata of the Animikie Group, which are interpreted to have been deposited after initial deformation of the fold-and-thrust belt but more or less concurrently with emplacement of the fold-and-thrust mass onto the margin of the Archean Superior craton. The southern panels of the fold-and-thrust belt contain deep-seated metamorphic and plutonic rocks characteristic of the internal zones of a collisional orogen.

Iron-formations appear to have been deposited at different times and under differing geologic conditions during tectonic evolution of the Penokean orogen. They are associated stratigraphically with volcanic rocks in the South range of the Cuyuna district, with euxinic black shale and argillite in the North range of the Cuyuna district, and with tidally deposited sandstone and siltstone on the Mesabi range. The Biwabik Iron Formation of the Mesabi range is younger than the various iron-formation units of the Cuyuna district, and the correlation of the Biwabik with the Trommald Formation is no longer valid.

## INTRODUCTION

Although the manifestations of plate tectonics are most readily demonstrated in currently active tectonic regimes and deformed belts younger than about 200 Ma, geologists increasingly recognize the Precambrian cratonic nuclei as the ultimate end products of tectonic processes that began with plate-margin interactions. Thus the insights obtained from tectonic studies of Phanerozoic orogens and Holocene mobile zones are increasingly being applied to the analysis of Precambrian deformed belts (e.g. Ernst, 1983; Kröner, 1985; Hoffman, 1988). Our plate-tectonic reinterpretation of the geology of the Animikie basin and contiguous Early Proterozoic terrane in east-central Minnesota follows the trend established by others who have worked recently in the Penokean deformed belt of Wisconsin and Upper Michigan (Sims and Peterman, 1983; Young, 1983; Larue, 1983; Morey, 1983; LaBerge and Myers, 1984; Larue and Ueng, 1985; Sims and others, 1985, 1987; Schulz, 1987).

The rocks of east-central Minnesota are very poorly exposed, and therefore conventional geologic mapping methods cannot be used except locally. Instead, mapping has relied on geophysical methods (chiefly aeromagnetic and gravity surveys), together with drilling data. This approach cannot lead to a totally objective rendering of the geology unless and until drilling has been completed on an unrealistically close-spaced grid—perhaps one with nodes as close as 100 meters in areas of complex stratigraphy and structure. Lacking that sort of control, any geologic map of the complicated, covered Penokean terrane will inevitably contain a large subjective component that reflects the education, philosophy, and biases of the authors. In this particular example, our major bias is the belief that plate-tectonic processes were responsible for the geological development of the area.

We are concerned in this report with the tectonic evolution of the western end of the Penokean orogen. The orogen is known to extend along the southern margin of the Archean Superior craton from central Minnesota to the Grenville Front, and appears to have been the locus of tectonic activity from before 2200 Ma to about 1760 Ma (Young, 1983). It is possible that the orogen does not end on the west in central Minnesota, but instead bends southward and again westward across northernmost Iowa. These speculative extensions beneath Phanerozoic cover remain to be confirmed, however.

We use the term *Penokean orogen* in the regional sense, with reference to a deformed belt that evolved through various stages over a long interval of Early Proterozoic time. This usage is analogous to the current usage of the term *Appalachian orogen* to describe the deformed belt that evolved between the Late Proterozoic and the Late Paleozoic along the eastern margin of North America (e.g. Williams and Hatcher, 1982), and is conceptually equivalent to the usage of *Trans-Hudson orogen* to describe another Early Proterozoic deformed belt along the northern and northwestern sides of the Superior Craton (Lewry and others, 1985). We restrict the term *Penokean orogeny* to the deformational and intrusive events of generally collisional nature that occurred toward the end of the evolutionary history of the Penokean orogen. In time terms, the Penokean orogeny is generally understood to have occurred between about 1900 and 1760 Ma, with the most intense activity having centered in the interval 1870-1850 Ma (Van Schmus, 1976; Van Schmus and Bickford, 1981). Conceptually, the Penokean orogeny is to the Penokean orogen as the Alleghanian orogeny is to the Appalachian orogen (Seacor and others, 1986).

It has been recognized for years that there are pronounced increases in stratigraphic and structural complexity, and also of metamorphic grade, from north-northwest to south-southeast across the regional trend of the Penokean orogen in Minnesota (see summary in Morey, 1983). These changes from one side of the orogen to the other are broadly similar in scale and degree to those observed from the cratonic foreland to the metamorphosed internal zones of the Appalachians and other collisional orogens of Phanerozoic age, and suggest a commonality of tectonic evolution. In Minnesota, a north-northwest to south-southeast transect of the Penokean orogen passes from essentially undeformed sedimentary rocks that lie directly on Archean basement along the northern margin of the Animikie basin, through zones of folded and thrust-faulted sedimentary and volcanic rocks in the southern part of the Animikie basin and the Cuyuna mining district, to the complex metamorphic-plutonic terrane of the McGrath-Little Falls area and beyond (Fig. 1).

Recently Hoffman (1987) has pointed out that several circum-Superior Proterozoic basins, including the Animikie basin, possess many attributes of migrating foredeeps or foreland basins (Beaumont, 1981). Because foreland basins develop as a flexural response to loading of the continental lithosphere by stacked thrust sheets (Price, 1973; Jordan, 1981; Davis and others, 1983; Quinlan and Beaumont, 1984), any particular foreland basin should be paired with a fold-and-thrust terrane that contains the tectonically interdigitated remains of island arcs, intra-arc basins, accretionary prisms, continental fragments, and possibly even seamount chains that were emplaced onto a continental margin during attempted subduction of continental crust (Fig. 2). The South range of the Cuyuna district and contiguous areas to the east and south contain geophysically revealed structural discontinuities that are probable zones of thrusting, and possess small-scale structural features consistent with the existence of large-scale, north-northwest-verging nappes (Holst, 1982, 1984, 1985). Therefore the belt of strongly deformed Early Proterozoic rocks that flanks the main bowl of the Animikie basin on the south (Fig. 1) could be the deeply eroded remains of the thrust mass responsible for


**Figure 1. Regional tectonic interpretation showing the tectonic elements and major geographic districts discussed in the text. The same map is printed in the marginal material of Plate 1.**

producing the Animikie basin as a flexural foredeep (Fig. 2). The Cuyuna terrane and the rocks southeast of it are interpreted to include the external, medial, and internal zones of a fold-and-thrust belt and to represent successively deeper tectonic levels toward the south.

Our reinterpretation of the Penokean orogen in Minnesota as consisting of a foreland basin (main bowl of the Animikie basin) paired with a fold-and-thrust belt is offered as a working hypothesis that requires additional substantiation and refinement.

## SYNOPSIS OF NEW WORK

The Early Proterozoic tectonic framework of the Animikie basin in east-central Minnesota, as mapped by Morey and others (1981), was based for the most part on pre-plate-tectonic concepts reminiscent of Beloussov (1962), wherein vertical tectonism was interpreted to have produced synclines and anticlines in a pattern of superimposed interference folds. In the 7 years since that time, the body of geophysical data and drill hole information pertaining to the area has grown substantially. A new high-resolution aeromagnetic survey of the region has been flown (Chandler, 1983a, b, c, 1985), and computer-prepared derivative maps and theoretical models based on the aeromagnetic data (Carlson, 1985) have extended the utility of the survey beyond qualitative interpretation. The process of converting the aeromagnetic data into a geologic map has been furthered by corroborative test drilling of two types. The scientific drilling program of the Minnesota Geological Survey has enabled us to test directly, by drilling through the glacially deposited overburden, the sources of particular aeromagnetic anomalies and anomaly patterns (Southwick, 1980; Southwick and others, 1986). Eighty-one shallow test holes were drilled within the map area under this program. In addition, iron-mining companies formerly active in the region have recently released several hundred exploration records and drill cores. These old data, some dating back to the period 1900-1910, have been especially valuable in deciphering the complex structure and stratigraphy of the Emily district and the South range of the Cuyuna district (Morey and Morey, 1986), where public information on the geology had formerly been scarce.

Four major insights have emerged from the new geophysical data and drilling. First, drilling has confirmed that the Virginia Formation of the Mesabi range is continuous with and passes directly into the Thomson Formation of northeastern Carlton County. The Virginia and Thomson together, therefore, comprise the main fill of the Animikie basin. Moreover, argillaceous sedimentary rocks probably correlative with these units extend about 40 km farther west and southwest than was previously realized, in what are now called the Long Prairie basin and the Nimrod outlier (Plate 1).

Secondly, there is clear evidence that iron sedimentation occurred at several different times and under varying geological conditions. Major iron-formations are associated stratigraphically with volcanic rocks in the South range of the Cuyuna district and the Glen Township area; with black shale and argillite in the North range of the Cuyuna district; and with tidally deposited sandstone and siltstone along the northern margin of the Animikie basin, on the Mesabi range (Ojakangas, 1983). The largest of these, the Biwabik Iron Formation of the Mesabi range, is also one of the youngest. It and the other sedimentary rocks of the Animikie Group occur above a major deformed unconformity that cuts across previously deformed, somewhat older sedimentary and volcanic rocks in the Cuyuna district. The Trommald Formation and other iron-formation units in a locally twice-formed sequence beneath the unconformity cannot be correlative with the Biwabik; they are separate stratigraphic entities. The folded sedimentary rocks of the North range of the Cuyuna district comprise a distinct stratigraphic package that rests with slight unconformity on still older rocks provisionally assigned to the Mille Lacs Group. Iron-formations within this oldest sequence include those near Philbrook (Boerboom, 1987), those near Randall and at various other places along the South range of the Cuyuna district, and those in the Glen Township area of Aitkin County. Where the intervening North range sequence is missing, the unconformity between the Animikie Group and the Mille Lacs Group (Morey, 1978) is a major tectonostratigraphic break.

Thirdly, there are several geophysically defined structural discontinuities in the southern part of the region, within and southeast of the South range of the Cuyuna district, across which demonstrable contrasts in metamorphic grade, stratigraphy, and structural style occur. The most pronounced of these are the Malmo structural discontinuity, which passes through Mille Lacs Lake, and the Serpent Lake structural discontinuity, which passes just south of Crosby (Plate 1). The Malmo discontinuity corresponds closely in position to a magnetotelluric feature recognized by Wunderman and Young (1987) and named by them the Malmo thrust. The discontinuities mapped on Figure 1 and Plate 1 are interpreted as tectonic boundaries, probably involving major thrust faults between slices of folded rocks.

Finally, the region henceforth referred to as the fold-and-thrust belt (Fig. 1) contains a much larger proportion of volcanic rocks than was heretofore realized. Sizable areas formerly thought to be underlain by metasedimentary rocks or granitoid gneiss, because of their subdued magnetic signature, are now known to be underlain mainly by mafic and intermediate metavolcanic rocks, which are weakly magnetic.

The four sets of observations enumerated above account for the major differences between Plate 1 and the earlier geologic map of Morey and others (1981).

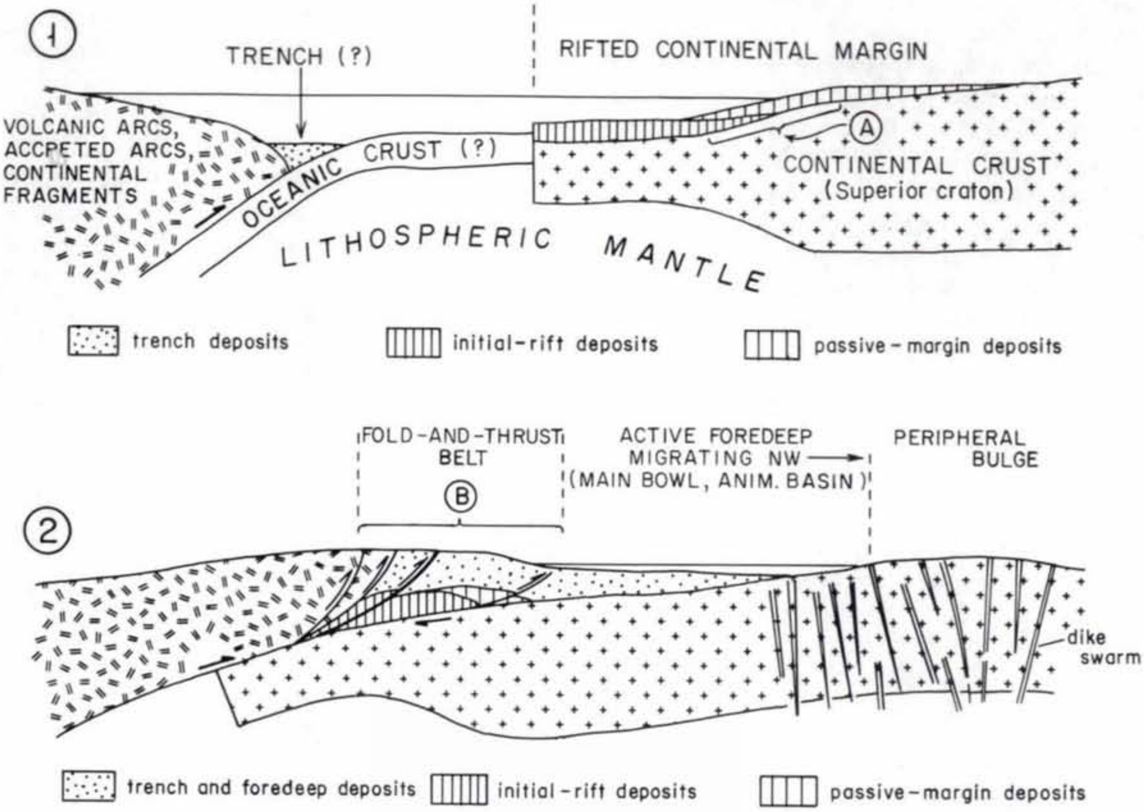


**Figure 2. Highly schematic diagram adapted from Hoffman (1987) illustrating the evolution of an oceanic trench (stage 1) into a foredeep (stage 2). With respect to the Penokean orogen in Minnesota, stage 1 could represent the rifted margin of the Superior craton approaching a southeast-dipping subduction zone in Early Proterozoic time. Initial-rift deposits laid down earlier are riding on the continental edge; passive-margin deposits, possibly preserved in the Denham Formation and other quartzose units of the Mille Lacs Group, are accumulating near (A). Stage 2 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 (A), as well as early deposits laid down toward the rear of the foredeep, also may be incorporated in the deforming mass. In the Penokean of Minnesota there is no unequivocal evidence for the prior existence of oceanic crust, trench deposits, or volcanic rocks of arc affinity within the fold-and-thrust belt. Therefore, this diagram must be considered as a possible mode of foredeep generations that has not been fully documented for the Penokean case.**

**The tectonic consumption of a back-arc basin rather than oceanic crust also could lead to the development of a foredeep, as discussed and illustrated further on in this report.**

## REGIONAL FRAMEWORK

The western end of the Penokean orogen in Minnesota consists of five geologically distinct elements. These are (1) the Archean rocks framing the orogen on the northwest, which comprise the basement on which at least part of the Early Proterozoic supracrustal sequence was deposited; (2) the Kenora-Kabetogama dike swarm, consisting of Early Proterozoic (ca. 2120 Ma) diabase dikes within the Archean basement, northwest of the outboard margin of the Early Proterozoic supracrustal rocks; (3) the main bowl of the Animikie basin, containing Early Proterozoic sedimentary rocks that lie unconformably on Archean basement and the Kenora-Kabetogama dike swarm along the Mesabi range, and on deformed earlier Proterozoic rocks along its southern margin; (4) two subsidiary basins analogous to the main bowl, here named the Nimrod outlier and the Long Prairie basin; and (5) a complexly deformed belt (fold-and-thrust belt) lying southeast of the Animikie basin and its equivalents that involves volcanic, sedimentary, and intrusive rocks of Early Proterozoic age, and also some Archean basement. The deformed belt can be subdivided further into four panels of internally consistent geology (Fig. 1). These are, from southeast to northwest, the McGrath-Little Falls panel, which contains medium- to high-grade metamorphic rocks, migmatite, and a variety of granitoid plutons, and displays structures characteristic of an internal tectonic zone; the Moose Lake-Glen Township panel and the Cuyuna South range panel, which together constitute a medial zone of complex overturned folds and thrust faults in low-grade metavolcanic and metasedimentary rocks; and the Cuyuna North range panel, which contains folded, fine-grained sedimentary rocks of very low metamorphic rank that have structural and stratigraphic attributes characteristic of an external tectonic zone.

In tectonic terms, the Archean basement northwest of the Penokean orogen constitutes the cratonic foreland, and the Kenora-Kabetogama dikes are a foreland dike swarm. The main bowl of the Animikie basin, the Nimrod outlier, and the Long Prairie basin are interpreted as the remnants of a migrating foredeep or foreland basin (Beaumont, 1981; Hoffman, 1987). The deformed belt southeast of the Animikie foredeep and its equivalents is a fold-and-thrust belt consisting of several tectonic slices or panels, each of which has its own stratigraphy and structural style and is bounded by structural discontinuities. The tectonic terminology we apply to the Penokean orogen in Minnesota is summarized in Figure 1 and also presented as a marginal illustration on Plate 1.

## DESCRIPTION OF THE TECTONIC ELEMENTS

In this section we describe the various tectonic elements recognized in the Penokean orogen.

### (1) The Cratonic Foreland

The rocks framing the Animikie basin on the north and west belong to two broadly dissimilar Archean terranes that are in contact along the Great Lakes tectonic zone (Sims and others, 1980; Fig. 1). The rocks north of the Great Lakes tectonic zone (GLTZ) have been referred to as the greenstone-granite terrane. This terrane consists chiefly of east-northeast-trending belts of low-grade supracrustal rocks and intervening belts of intrusive granitoids of late Archean age, a pattern characteristic of most of the Superior province of the Canadian Shield (Superior craton of Hoffman, 1988). In contrast, the Archean terrane south of the GLTZ is mainly high-grade quartzofeldspathic gneiss, presumably equivalent to the middle Archean gneiss complex exposed in the Minnesota River Valley, and late Archean granitoid intrusions. This Archean gneiss terrane is very sketchily known within the map area.

Archean rocks belonging to the Giants Range batholith and a narrow supracrustal belt just south of it are exposed north of the Mesabi range, between Nashwauk and Biwabik in the northeastern corner of the map area. The basal units of the Early Proterozoic Animikie Group lie unconformably on these Archean rocks, and the basal unconformity can be examined in outcrop at several localities (Morey, 1972; Ojakangas, 1983).

West and southwest of the Animikie basin the Archean greenstone-granite terrane is thickly covered by Quaternary glaciogenic deposits. Metavolcanic rocks encountered by shallow drilling in this area include pillowed metabasalt, intermediate to mafic volcanic breccia and tuff, and hypabyssal, presumably subvolcanic, intrusions of metadiabase and dacite porphyry. Substantial amounts of volcaniclastic sedimentary rocks also occur there, as do thin units of laminated magnetite-chert iron-formation. These rocks are generally of low metamorphic grade and are comparable in all respects to common supracrustal lithologies in the "greenstone belts" of the exposed Superior craton.

A major belt of Archean supracrustal rocks about 30 km wide that abuts the GLTZ on the north (Plate 1) corresponds to a sharply bounded zone of low, broad magnetic anomalies. The southern edge of another supracrustal belt lies more or less along the northwestern margin of the map area. The area between these belts is occupied chiefly by granitoid rocks that are the buried southwestward extension of the Giants Range batholith.

Intrusive rock types directly observed in the poorly exposed western part of the greenstone-granite terrane include hornblende metagabbro, foliated biotite-hornblende tonalite, biotite monzogranite, gneissose biotite-hornblende granodiorite, and appinitic diorite. The foliated biotite-hornblende tonalite forms several small, ovoid plutons within the southernmost supracrustal belt. Zircons from two of these, near Staples and Browerville, yield U-Pb ages of 2688 ± 72 Ma (Z.E. Peterman, unpub. data). Farther north, irregularly shaped large plutons composed of monzogranite, granodiorite, granite, and their migmatitic border phases surround and underlie the Nimrod outlier (Plate 1). These granitoids can be traced geophysically to the northeast into exposed rocks of the Giants Range batholith.

Small plugs of appinitic diorite (see Hall, 1967, for discussion of term) pepper the area of Archean supracrustal rocks within the structural divide between the Long Prairie basin and the main bowl of the Animikie basin (Plate 1). These quartz-poor, hornblende-rich rocks are petrographically similar to the syenite and monzodiorite plutons of the Vermilion district (Sims and Mudrey, 1972) and to the "sanukitoid suite" of Shirey and Hanson (1984). The appinite plutons are essentially undeformed, and their form and distribution, as judged from aeromagnetic mapping, strongly imply that they are late-tectonic or perhaps post-tectonic with respect to Archean deformational events. We assume, from analogy with better exposed areas of the Superior craton, that the appinite intrusions are of late Archean age, and mark the end of Archean plutonism in this region. Without radiometric evidence, however, it is impossible to rule out a Proterozoic age for some of the appinitic plugs.

Drilling in the Archean terrane south of the GLTZ has encountered tonalite gneiss, biotite paragneiss with leucogranite leucosomes, and intrusions of biotite-hornblende tonalite (Southwick and others, 1986). Biotite-sillimanite paragneiss and coarsely megacrystic granitic gneiss are known from drill holes a short distance west of the map area. All of these rocks are lithologically, structurally, and geophysically similar to components of the well-studied gneissic terrane exposed in the Minnesota River Valley (Goldich and others, 1980a, b; Goldich and Wooden, 1980; Wooden and others, 1980), and are assumed to be broadly correlative with them. This tentative correlation, across a covered area more than 100 km wide, has not been confirmed radiometrically, and some of the gneisses may be Early Proterozoic (Horan and others, 1987).

The GLTZ itself is indicated geophysically by a seismic reflector dipping northward at 30° that projects down dip to mid-crustal level (Gibbs and others, 1984). This reflector intersects the earth's surface near the trace of the Morris fault, which Morey and Sims (1976) recognized as a major crustal boundary on the basis of its aeromagnetic and gravity expression and the marked differences in metamorphic, lithologic, structural, and isotopic attributes of the rocks on either side. The GLTZ was interpreted by Gibbs and others (1984) as a south-directed thrust zone which brought late Archean volcanic arc complexes (represented by the greenstone-bearing supracrustal belts of the Superior craton) into tectonic contact with an older continental mass (represented by the Archean gneiss terrane). Alternatively, it could be interpreted as an extensional shear zone of the sort discussed and diagramed by Wernicke (1985) or Lister and others (1986), in which case it may have been an instrumental structure during the extensional stage of development of the Penokean orogen. Regardless of its origin, the GLTZ appears to be a major crustal discontinuity that was established in late Archean or very early Proterozoic time and acted subsequently as a zone of crustal weakness (Sims and others, 1980). The zone trends beneath the medial zone of the Penokean fold-and-thrust belt (Fig. 1), implying its active or passive participation in Penokean tectonism.

### (2) The Kenora-Kabetogama Dike Swarm

Essentially undeformed, weakly altered diabase dikes (Rb-Sr age = 2120 ± 67 Ma; Beck and Murthy, 1982) collectively form the Kenora-Kabetogama (KK) swarm (Halls, 1982; Southwick and Day, 1983) within the cratonic foreland north and west of the Animikie basin (Plate 1). These dikes and their wall rocks crop out sporadically north of the Mesabi range, but most of the swarm is concealed by Quaternary glacial deposits. Prominent linear, northwest-trending magnetic anomalies are associated with the dikes, and the profusion of such anomalies in the poorly exposed area west and northwest of the Animikie basin indicates that the dike swarm is at least 300 km long and 300 km wide (Chandler and Southwick, 1985; Southwick and Halls, 1987). Near Nashwauk, basal beds of the Pokegama Quartzite lie unconformably on an erosionally truncated dike and thereby establish that the KK dike swarm was emplaced before the deposition of sedimentary rocks in the main bowl of the Animikie basin (Southwick and Day, 1983). The aeromagnetic anomalies associated with the dikes broaden and flatten upon crossing into the main Animikie basin, the Nimrod outlier, and the Long Prairie basin, and eventually disappear toward the basin interiors. This damping out of aeromagnetic expression is consistent with increasingly deep burial of the dikes beneath sedimentary fill, and is strong evidence on a regional scale for the unconformable relationship between the sedimentary fill in the basins and the underlying KK dikes. Aeromagnetic anomalies associated with the dikes trend uninterruptedly across the GLTZ, indicating that major displacements on the GLTZ had ceased prior to dike intrusion. The anomalies appear not to extend beyond the Appleton geophysical lineament (Plate 1).

### (3) Main Bowl of the Animikie Basin

The northern part of the Animikie basin is occupied by the Animikie Group, a sedimentary sequence dipping gently southward that rests directly on Archean basement and the erosionally truncated KK dike swarm. At the base of the sedimentary section is the Pokegama Quartzite, which is overlain successively by the Biwabik Iron Formation and the Virginia Formation. The Virginia Formation and its approximate correlative the Thomson Formation together constitute a very thick accumulation of rhythmically interbedded mudrocks, siltstone, and graywacke that has the sedimentary attributes of an orogenic turbidite deposit (Morey and Ojakangas, 1970; Lucente and Morey, 1983). Sparse drilling suggests that the graywacke component of the turbidite sequence forms progressively thicker and coarser beds from north to south across the basin.

Deformation of the Virginia and Thomson Formations increases systematically from north to south. Incipient slaty cleavage first appears about 15 km south of the Mesabi range, where the rocks are thrown into broad, open folds (Marsden, 1972; Southwick, 1987). The cleavage strengthens and the folds tighten progressively southward across the basin from that point. At Thomson Dam in eastern Carlton County, toward the south margin of the basin, the folds are upright and moderately tight, and the regional cleavage is pervasive, subvertical, east-striking, and axial-planar to the folds (Wright and others, 1970; Holst, 1982, 1984).

Stratigraphic and structural relationships are imperfectly known at the southwestern closure of the main bowl in the so-called Mesabi-Cuyuna gap, owing to the very thick glacial cover. Aeromagnetic patterns and scattered drill hole information in the gap suggest that the erosionally truncated basal contact of the Animikie Group is about 10 km west of its position as shown on the 1981 geologic map (Morey and others, 1981). Furthermore, it is now clear that the basin margin has been displaced northward about 17 km relative to the trend of the Mesabi range on the western side of a previously unrecognized northwest-trending fault located about 2 km northeast of Remer (Plate 1). The Biwabik Iron Formation thins to the west along the Mesabi range, and apparently continues to thin as it curves around the western end of the basin west of the fault. South of the gap the stratigraphic position of the Biwabik is occupied by three broadly lenticular iron-formation units that are separated from one another by intervening sequences of black argillite. The lowermost of these was mapped as the Biwabik by Marsden (1972), who referred to the two higher iron-formation units as the Emily iron-formation. Morey (1978) proposed that the Biwabik of the Emily district, as defined by Marsden (1972), correlated with the Trommald Formation in the North range of the Cuyuna district. Morey also correlated the Emily Member of the Rabbit Lake Formation (Marsden, 1972) with an unnamed unit of iron-formation in the lower part of the Virginia Formation. In this scheme, the third iron-formation of the Emily district was yet another unnamed unit in the Rabbit Lake Formation. We now prefer to think of all three iron-rich lenses in the Emily area as informal units that together occupy the approximate stratigraphic position occupied by the Biwabik Iron Formation on the Mesabi range.

The map geometry of the Emily area (Fig. 1 and Plate 1), as inferred from aeromagnetic maps and drilling, strongly implies that the basal contact of the Animikie Group is an unconformity cut onto older folded rocks of the Cuyuna district. The unconformable relationship proposed here is supported geophysically by a Poisson analysis of gravity and magnetic data carried out by Carlson (1985), which detected the anomaly patterns characteristic of the folded rocks of the Cuyuna district beneath the main bowl of the Animikie basin far northeast of their surface termination. Earlier, Marsden (1972) and Morey (1978) both concluded that the Animikie Group rested unconformably on an older sedimentary sequence in the Emily area. However, their inferred geographic location, stratigraphic position, and degree of structural discordance of the unconformity differ substantially from the interpretation proposed here.

We suggest that the unconformity at the base of the Animikie Group trends more or less east-southeast from Ross Lake (Plate 1), sharply truncating the east-northeast grain of the folded rocks in the North range of the Cuyuna district, and then trends more or less eastward across Aitkin and Carlton Counties. An important consequence of this interpretation is that the folded rocks of the North range cannot be correlative with the Animikie Group. The Mahnomen Formation, Trommald Formation, and Rabbit Lake Formation, formerly correlated with the Pokegama, Biwabik, and Virginia/Thomson, respectively (Marsden, 1972; Morey, 1978; Morey and others, 1981), must instead be somewhat older. We note with interest that a similar stratigraphic relationship, also based on structural interpretations, was first proposed by Zapffe (1925; also 1933).

The map position of the sub-Animikie unconformity becomes problematic in Carlton County, where it trends more or less parallel to the dominant east-trending tectonic grain in subjacent rocks. We suggest that the unconformity may be located a short distance south of Otter Creek, where Winchell (1899) inferred an unconformity between micaceous schists on the south and presumably younger, dark-colored conglomeratic slate on the north.

Recent outcrop mapping and drilling have shown that the Otter Creek area is indeed the locus of an abrupt transition, and possibly a sharp contact, between contrasting rock types. Holst (1982, 1984) has noted a significant change in structural geometry near, but not exactly coincident with, the inferred position of the unconformity. The rocks to the north of Holst's line (Plate 1) are singly cleaved, once-folded argillaceous slate and graywacke of the Thomson Formation; the rocks immediately south of Holst's line are Thomson Formation that has undergone subhorizontal recumbent folding followed by a second folding of upright style. These doubly folded slaty rocks pass southward into higher grade doubly foliated muscovite schist, muscovite-chlorite phyllite, and a variety of amphibole-bearing metavolcanic rocks. Holst inferred that the transition from twice-deformed phyllitic rocks to singly cleaved slaty rocks marked the approximate front of a north-directed nappe structure. We concur in this view (Morey and Southwick, 1984), but further suggest that the position of the nappe front may have been a basin margin, and thus the locus of unconformable sedimentation during tectonic compression (Fig. 2).

Most geologists since Winchell (1899) have regarded the belt of rocks south of Otter Creek in Carlton County as the more highly metamorphosed equivalent of the Thomson Formation (e.g., Hall, 1901; Schwartz, 1942). However, the metasedimentary rocks of this area differ from the Thomson Formation at its type locality in bedding characteristics and composition (paucity of graywacke layers thicker than a few centimeters; local presence of green, chlorite-rich beds of probably volcanic derivation), as well as in structural style and metamorphic grade. In addition, metabasalt flows, metadiabase sills, and various kinds of mafic to intermediate volcaniclastic rocks are interbedded with the metasedimentary rocks south of Otter Creek, further suggesting the likelihood of a volcanic contribution to the metasedimentary materials. For these reasons we resurrect Winchell's conclusion that the rocks south of Otter Creek are stratigraphically distinct from, and older than, the Thomson Formation at its type locality, and are separated from it by an obscure unconformity. Tectonically the rocks south of Otter Creek are considered to be part of the fold-and-thrust belt, not the main bowl of the Animikie basin.

**(4) The Nimrod Outlier and Long Prairie Basin**

These extensions of the Animikie basin to the west (Fig. 1) were first recognized from detailed aeromagnetic surveying and later investigated by drilling. Aeromagnetically they both resemble the main bowl of the basin in that they are magnetically flat and featureless. Magnetic signatures associated with the Kenora-Kabetogama dikes and various Archean rock units decrease in amplitude and increase in width at the margins of the magnetically flat areas, implying that the dikes and Archean rocks pass beneath a thick covering of virtually nonmagnetic sedimentary rock. The straight and abrupt western margin of the Nimrod outlier suggests control by a north-northwest-trending fault. Similarly, a major northwest-trending fault appears to mark part of the southwestern contact of the Long Prairie basin.

Drilling has confirmed that the Nimrod outlier contains almost flat-lying laminated argillite that is identical lithologically to the Virginia Formation in the vicinity of the Mesabi range. We infer, therefore, that the Nimrod is simply an erosional remnant of Animikie Group rocks lying unconformably on Archean basement. No direct evidence has been found for the presence of the Pokegama Quartzite or Biwabik Iron Formation at the margins of the outlier. The Biwabik, if present at all, must be a nonmagnetic facies, an attribute typical of the western part of the Mesabi range.

The Long Prairie basin also contains laminated argillite and graywacke that are similar in all respects to the rocks of the Virginia and Thomson Formations in the main Animikie basin. Furthermore, drilling confirms a northwest-to-southeast increase in deformation that is very similar to the north-to-south structural progression in the main bowl (Southwick, 1987) and a concomitant increase in metamorphic recrystallization. We infer, therefore, that the Long Prairie basin is a stratigraphic and structural analog of the main Animikie basin that lies outboard of the fold-and-thrust belt on the west. A red arkosic quartzite interpreted to be the stratigraphic equivalent of the Pokegama Quartzite was encountered in drilling near Pillager at the eastern edge of the basin. Otherwise, there is no direct evidence of the lower formations of the Animikie Group in the Long Prairie basin, and here too, the Biwabik Iron Formation, if present at all, must consist of a nonmagnetic facies.

A drill hole located near Lake Alexander, at the eastern edge of the Long Prairie basin in Morrison County, encountered a deformed polymictic conglomerate composed of pebbles derived from sedimentary and volcanic rock units within the fold-and-thrust belt to the southeast (Southwick and others, 1986, p. 102-103). This sample implies that sedimentation in the Long Prairie basin occurred after, and perhaps during, deformation and uplift of the fold-and-thrust belt. The conglomerate itself is not viewed as a basal unit, but rather as a channel deposit within a submarine fan complex that was fed from a tectonic source area lying to the southeast. In this interpretation, the contact between the fill of the Long Prairie basin and the tectonic hinterland on its southeastern side is a complex tectonostratigraphic surface recording dynamic interactions between concomitant deformation and deposition. In contrast, the contact between basin fill and the Archean rocks on the northwestern, foreland side is a conventional unconformity.

**(5) The Fold-and-Thrust Belt**

The rocks of this terrane are much more complex both stratigraphically and structurally than those in the main bowl of the Animikie basin or its outliers. All of them except the post-orogenic plutonic rocks in the southern part of the belt are metamorphosed and foliated, and have been strongly deformed by folding and faulting. Geographically, the fold-and-thrust belt includes the Cuyuna district and a broad arc of country south and east of it that extends roughly from western Morrison County at the western end to southern Carlton and northern Pine Counties at the eastern end. The southern boundary of the belt has not been established; it lies beyond the southeastern margin of the map area.

The structural geology of this region was interpreted by Morey (1978, 1983) and Morey and others (1981) to consist primarily of a sequence of well-ordered, northwest-inclined anticlines and synclines (Fig. 3). The folds were interpreted to become more open and upright toward the northwest, and the degree of basement involvement in the deformation was also thought to decrease from southeast to northwest. The stratified rocks affected by folding were divided by Morey (1978) into the Mille Lacs Group (older) and the Animikie Group (younger), which were separated by an unconformity of such low angular discordance that the formations above and below the unconformity surface retained essentially parallel geometry within major fold structures.

The Mille Lacs Group was defined by Morey (1978) to consist of five formations (Fig. 4), which included quartz-rich clastic sedimentary rocks together with iron-formation and assorted volcanic rocks in the lower part, and quartz wacke together with minor dolomite and volcanic material in the upper part. The Mille Lacs section was envisaged to thicken irregularly toward the southeast, and to thin to zero thickness or be upfaulted and eroded away near the northern boundary of the Great Lakes tectonic zone (Morey, 1983).

It is now far from certain that the rock units assigned by Morey (1978) to the Mille Lacs Group do in fact constitute an ordered, cohesive stratigraphic sequence. Mille Lacs Group rocks subcrop primarily in the medial and internal zones of the fold-and-thrust belt (Fig. 1), where they have been tectonically dismembered into several slices that are bounded by structural discontinuities. It is likely that tectonism has divided some stratigraphic intervals that originally were conformable, and combined others that originally were separated in space and age. Stratigraphic complexities introduced by tectonism are difficult enough to decipher in areas of good outcrop; in areas of minimal exposure, such as east-central Minnesota, they become even more intractable. Therefore we have deemphasized the stratigraphic unity implied by the concept of the Mille Lacs Group, although we continue to use the term in a generalized way and to recognize some of the rock units that were included in its definition originally.

The central panels of the fold-and-thrust belt, that is, the South range of the Cuyuna district and the Glen Township-Moose Lake terrane east of Lake Mille Lacs, contain considerably more volcanic material than had been recognized previously (Fig. 5 and Plate 1). The volcanic rocks are mostly of mafic to intermediate composition and include pillowed flows, fragmental rocks of various kinds, and subvolcanic sills of diabasic texture. These occur in close stratigraphic association with dark-colored graphitic and sulfidic schist; iron-formation of silicate, carbonate, oxide, and sulfide facies; and, locally, quartz-rich clastic rocks. The three-part association made up of interlayered volcanic rocks, graphitic schist, and iron-formation was mapped as the Glen Township Formation and the Randall Formation by Morey and others (1981); the area occupied by this association, however, was substantially under-represented on the 1981 map.

Scientific and exploration drilling have shown that volcanic rocks also occupy large areas of the central panels that were formerly interpreted to contain metasedimentary schist or granitoid gneiss (Morey and others, 1981). The volcanic rocks of these areas are mostly, if not entirely, weakly magnetic metabasalt and compositionally related metadiabase. They occupy a large area in southern Aitkin County that had been mapped as a structural dome cored by presumed Archean gneiss, a major part of Carlton County that had been mapped as Thomson Formation, and several smaller areas within and near the South range that had been mapped as various metasedimentary units. The aeromagnetic signature over all of these areas is smooth and subdued.

Volcanic rocks are only a minor component of the lithostratigraphic succession on the North range of the Cuyuna district (Grout and Wolff, 1955; Schmidt, 1963; Marsden, 1972). Moreover, the rocks of the North range are less strongly foliated than those of the South range and other parts of the fold-and-thrust belt, and they are less recrystallized metamorphically. Structurally the North range is a complex synclinorium that is inclined toward the northwest (axial surfaces dip southeast) and is doubly plunging on a regional scale (Schmidt, 1963). The structure is outlined by several discrete layers of iron-formation that are interstratified with dark-colored, fine-grained argillite and slate (Morey and Morey, 1986). Formerly the sedimentary rocks in the North range synclinorium were correlated with the Animikie Group by Morey (1978), and the synclinorium was viewed as a deformed arm or bay of the main Animikie basin. However, as discussed in the previous section, we now conclude that the rocks of the main Animikie basin lap unconformably across the northeastern end of the North range synclinorium.

The stratigraphic position of the North range sedimentary succession with respect to the metavolcanic-rich succession in the central panels of the fold-and-thrust belt is not known. The basal rocks of the North range sequence lie unconformably on a poorly defined older sequence of sedimentary and volcanogenic strata, perhaps equivalent in part to the Denham Formation (Morey, 1978). The southern boundary of the North range panel is inferred from geophysical evidence to be tectonic. Linear magnetic trends associated with iron-formation and volcanic units in the South range panel cut across and truncate linear magnetic trends associated with iron-formation units in the North range panel. The discordant boundary between the North range and South range panels is here named the Serpent Lake structural discontinuity.

The southernmost panel of the fold-and-thrust belt (the McGrath-Little Falls panel) contains a variety of schistose

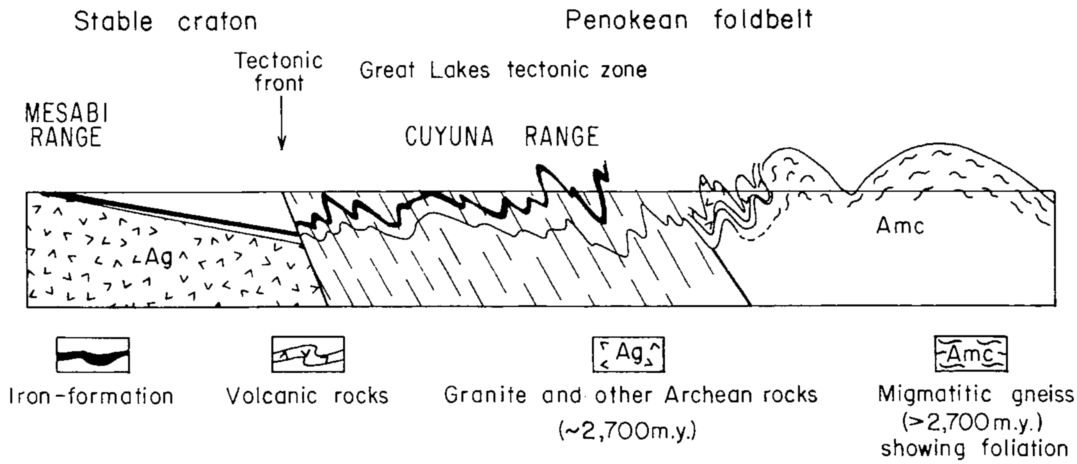


**Figure 3. Schematic cross section of the Penokean orogen taken from Morey (1983) showing the regional southeast-to-northwest change from tight, overturned folds to open, upright folds. Our present interpretation invokes considerable thrusting and tectonic imbrication of stratigraphic units in the southern segment of this section.**

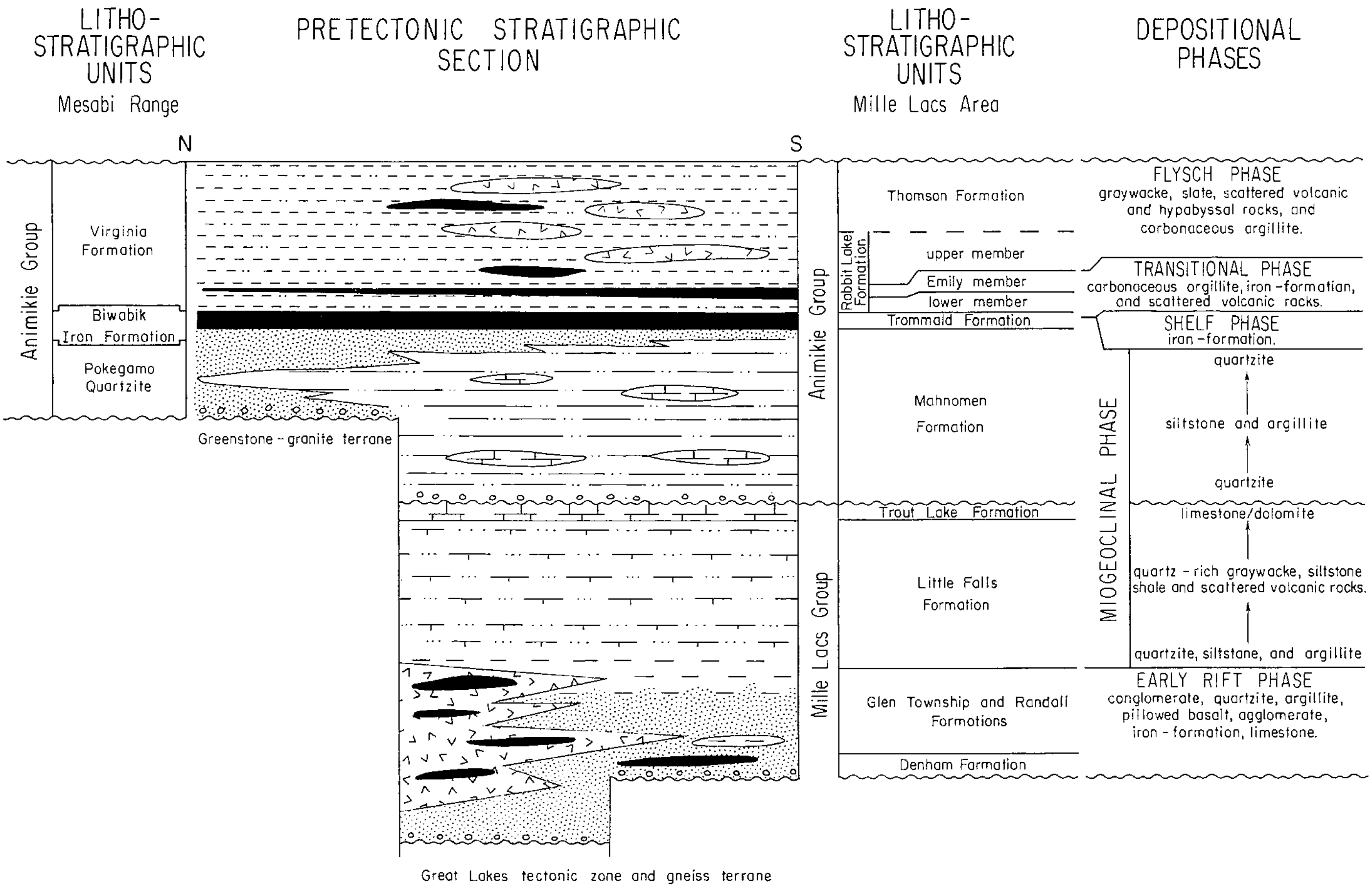


**Figure 4. Lithostratigraphic summary and schematic pretectonic section for the Penokean orogen as interpreted by Morey (1983). This interpretation depends explicitly upon the equivalency of the Biwabik and Trommald Iron Formations, which is no longer supported by the geologic and geophysical evidence. The Pokegama Quartzite is now interpreted to rest unconformably on rocks of the Mahomen Formation. See text for details.**

and gneissic rocks of obscure origin and equivocal age (Horan and others, 1987) and also a variety of Early Proterozoic granitoid plutons (age range approximately 1770-1870 m.y.; Spencer and Hanson, 1984; Goldich and Fischer, 1986). Among the gneissic rocks are the McGrath Gneiss, which is an Archean rock that was remobilized into the core of a Penokean gneiss dome (Stuckless and Goldich, 1972; Morey, 1978), and the Hillman Migmatite, a complex unit that may contain components of late Archean and Early Proterozoic age (Morey, 1978; Tasker, 1983). These rocks are interpreted to abut the much lower grade rocks to the north along a major tectonic contact that abruptly truncates geophysical anomalies associated with units of iron-formation and metavolcanic rock in the lower grade terrane. This boundary is here named the Malmo structural discontinuity, following the usage of Wunderman and Young (1987), who recognized a major zone of south-dipping magnetotelluric conductors along its trend.

In summary, the fold-and-thrust belt is interpreted to consist of four tectonically bounded slices or structural panels. The southernmost of these consists mainly of gneiss and relatively high-grade metasedimentary schist, together with granitoid plutons of Early Proterozoic age. The central two panels, the South range of the Cuyuna district and a large, arcuate area southeast of it that extends roughly from Glen Township to Moose Lake, consist primarily of folded and faulted metavolcanic and metasedimentary rocks of moderate to low metamorphic grade. The northwesternmost panel, containing the North range of the Cuyuna district, consists of folded, weakly metamorphosed sedimentary strata. The overall picture is one of decreasing tectonic depth and decreasing deformational complexity from southeast to northwest.

Iron-formations deposited in close association with mafic volcanism under euxinic conditions of sedimentation, perhaps early in the history of basin development, now reside in the folded and thrust-faulted terrane of the central two structural panels. Other iron-formations were deposited under quiescent conditions, in close association with the sedimentation of fine-grained, carbonaceous, argillaceous muds, in a small basin ancestral to the North range synclinorium of the Cuyuna district. A third episode of iron sedimentation occurred in the main bowl of the Animikie basin at a later time in the tectonic evolution of the Penokean foldbelt.

### Detailed Description of the McGrath-Little Falls Panel

The southernmost panel to be recognized so far in the fold-and-thrust belt contains several types of gneiss, amphibolite-facies metasedimentary schist, and a variety of granitoid intrusions ranging from tonalite to potassic granite in composition. Dome-and-basin structural geometry is well documented in the McGrath dome, which is cored by the McGrath Gneiss of Archean age and flanked by metamorphosed supracrustal rocks assigned to the Early Proterozoic Denham Formation (Morey, 1978; Holm, 1986). Although less obvious, dome-and-basin structural style also appears to be common in the poorly exposed region underlain by the Hillman Migmatite (Morey, 1978; Tasker, 1983), particularly in the immediate neighborhood of the larger Proterozoic intrusions. The aeromagnetic patterns of this region strongly imply that the Freedhem Granodiorite, Pierz Granite, Bradbury Creek Granodiorite, and several other unexposed and unnamed plutons all occupy the cores of domal structures in the Hillman. Where sufficiently exposed for mapping, these plutons possess an internal structural fabric of aligned mineral grains and xenoliths that is more or less parallel to their contacts. This, plus their inferred setting within structural domes, leads us to conclude that the Freedhem and related plutons are syntectonic to late-tectonic diapirs.

The contact between the metasedimentary schist of the Little Falls Formation and the Hillman Migmatite is not exposed and has not been penetrated by drilling. It has been variously interpreted by previous workers as an unconformity between supracrustal rocks and basement, and also as a metamorphic and intrusive boundary between unmigmatized rocks (the Little Falls) and strongly migmatized and injected rocks (the Hillman). In the first interpretation, the Hillman would be significantly older than the Little Falls and could be of Archean age (Morey, 1978), whereas in the latter (Keighin and others, 1972), the melanosome of the Hillman would be identical in age to the Little Falls, and the leucosome could be somewhat younger. Goldich and Fischer (1986) have obtained a zircon age of 1869 $\pm$ 5 Ma on a homogeneous, tonalitic phase of the Hillman, which indicates that at least a fraction of the leucosomatic material in the migmatite is of Proterozoic age. At the present time, however, there are no published radiometric or geochemical data bearing directly on the age of the melanosome or the gneissose leucosome of strongly heterogeneous composition that is intimately associated with it. These components of the migmatite are intruded by the more uniform tonalitic rock dated by Goldich and Fischer (1986) and therefore must be older.

Earlier workers noted that the rocks at Little Falls grossly resemble the Thomson Formation (Animikie Group) in that, prior to metamorphism, both units were thick sequences of rhythmically interbedded shale and graywacke that contained abundant carbonate concretions at certain favorable zones (Harder and Johnston, 1918; Schwartz, 1942; Goldich and others, 1961; Keighin and others, 1972). Morey (1978) agreed that the Little Falls Formation was probably Early Proterozoic in age, largely because it is not migmatized and is similar in its lithic and structural attributes to other metasedimentary rocks of Early Proterozoic age, but he disputed the Little Falls-Thomson correlation. His conclusion was based on the fact that the two units differ consistently in the modal composition of their contained graywacke beds, and the inference that the Little Falls lay unconformably on basement (i.e., Hillman), whereas the Thomson was higher in the stratigraphic sequence.

The Little Falls Formation is now interpreted to be in fault contact with argillaceous rocks of the Long Prairie basin, which are correlated with the Virginia-Thomson sequence of the Animikie Group on the basis of lithology and similar tectonostratigraphic position with respect to the cratonic foreland. This strengthens Morey's conclusion that the Little Falls rocks are not part of the Animikie Group. However, serious uncertainties remain as to the true stratigraphic position of the Little Falls Formation. It may be of some significance that staurolite-biotite schist from near Bristol, North Dakota, which markedly resembles the Little Falls material, yields an Archean age (Richards and others, 1986). Thus, the Little Falls Formation could be an Archean unit and the Little Falls-Hillman package could be entirely Archean in age. Clearly, radiometric and isotopic studies of the Little Falls and Hillman are sorely needed to sort out the various possibilities.

Postkinematic plutons of granite and granodiorite were emplaced into the McGrath-Little Falls structural panel at approximately 1770 Ma (Spencer and Hanson, 1984), and these appear to have marked the end of Penokean tectonic activity in the region. The large intrusion that includes the Isle and Warman Granites in the southeastern part of the map area (Plate 1) is of this general age and type; it is the northernmost of several similar granite bodies that are distributed within a broad area between Lake Mille Lacs and the vicinity of St. Cloud, some 65 km to the southwest (Morey 1978; Morey and others, 1981). In addition to the granitoid intrusions, a swarm of small ultramafic plugs or pipes (diameters typically 0.5-1 km) was emplaced into the terrane following its deformation (Southwick and Chandler, 1987). These plugs bear some similarities to kimberlite pipes in their form and distribution, although true kimberlite has not yet been identified in any of them. The ultramafic bodies are assumed to be part of the late Penokean magmatic suite, but neither their relationship to late Penokean granitoids nor their radiometric age has been established.

### Detailed Description of the Moose Lake-Glen Township Panel

This panel is the southeastern one of two that together form the medial zone of the fold-and-thrust belt. It extends from the Moose Lake-Barnum area of Carlton County on the east to the general vicinity of Shephard, in southern Crow Wing County, on the west. Its contact with the McGrath-Little Falls panel on the south is the Malmo structural discontinuity (Wunderman and Young, 1987), a geophysically distinct truncation of structural trends that coincides spatially with a substantial and steep metamorphic gradient along part of its length. Geophysically the panel encompasses local areas of sharp, linear magnetic and gravity anomalies that have attracted iron ore and base metal exploration, such as in the Glen Township area of southern Aitkin County and the Moose Lake-Kettle River area of Carlton County, and large areas of weak geophysical expression, limited and difficult surface access, and very sparse drilling coverage. In many ways the geology of the Moose Lake-Glen Township panel is the most enigmatic to be found in the Penokean orogen in Minnesota.

The Glen Township area (T. 46 N., R. 25 W. and its surroundings) is the type locality of the Glen Township Formation, defined by Morey (1978) from extensive industrial drilling data. The formation consists of coarsely interstratified metavolcanic rocks, metadiabase, graphitic schist, and iron-formation; these rock types form a sequence that is interlayered on a still larger scale with quartzite (the Dam Lake quartzite of informal industry usage; see Grout and Wolff, 1955, p. 86) and with thick, unnamed units of more homogeneous metabasalt and graphitic schist.

The complex map pattern inferred for the Glen Township area is based on aeromagnetic data and industry drilling (the latter mainly by the M.A. Hanna Company). It is consistent geometrically with the refolding of an earlier, northeast-trending antiform-synform pair by later folds that trend lightly north of east. A similar pattern on a larger scale was inferred for the area southwest of Glen Township on the northwestern side of Lake Mille Lacs. These patterns suggest the presence of a northeast-trending, southwest-closing, northwest-verging major fold that has been refolded by east-trending, later folds. The rather bizarre map pattern deduced for the area north of Lake Mille Lacs (Plate 1) is an interpretation clearly in need of further documentation. Nevertheless, the pattern is consistent with regional aeromagnetic trends, with drilled-out geology near Glen Township, and with the conclusion of Holst (1982, 1984) that two generations of folding have affected the mica schist that crops out near Moose Lake in the same structural panel about 70 km to the east.

The Early Proterozoic rocks of the Moose Lake-Kettle River-Barnum area were shown on the 1981 map as the Thomson Formation of the Animikie Group. As discussed in the foregoing section on the main bowl of the Animikie basin, we now interpret the Thomson to extend no farther south than Otter Creek. This leaves the graphitic muscovite-chlorite phyllite and schist near Barnum and Atkinson, the metamorphosed volcanic and hypabyssal rocks near Kettle River, and the mica schist (locally garnetiferous) near Moose Lake as unnamed units that are presumably older than the Thomson and unconformably beneath it (McSwiggen, 1987). The mafic and intermediate metavolcanic rocks near Kettle River are part of an extensive belt that has been traced westward by drilling as far as T. 46 N., R. 22 W., in southeastern Aitkin County, and is inferred from geophysics to go much farther. Similarly, the graphitic rocks on the northern side of the metavolcanic unit have been traced by drilling and were extrapolated by geophysics for some distance to the west. The mica schist south of the metavolcanic unit can be projected westward with far less confidence, owing to the paucity of drilling control and geophysical definition. It is shown extending as far west as the southernmost part of T. 45 N., R. 24 W., but its actual extent could be substantially greater or less than that.

In the absence of concrete evidence to the contrary, the mica schist of the Moose Lake area is assumed to be correlative with the schist that overlies the Denham Formation on the north flank of the McGrath dome in the McGrath-Little Falls panel (Plate 1; Fig. 1). We think it is likely, however, that the tectonic boundary between structural panels occurs within the schist sequence, along the trend of a sharp, east-trending linear magnetic anomaly located about 2.5 km north of Arthyde. Therefore, the section of mica schist between Denham and Moose Lake may have been thickened by tectonic imbrication, or it may consist of originally unconnected pelitic sequences that were brought together tectonically.

**Detailed Description of the Cuyuna South Range Panel**

The northern panel of the medial zone of the fold-and-thrust belt extends from the neighborhood of Hassman in Aitkin County on the northeast to the vicinity of Randall in Morrison County on the southwest. The rocks within it have been divided into three mappable units, consisting of: (1) more or less uniform metabasalt; (2) a complex sequence composed of mafic volcanic and hypabyssal rocks, graphitic slate or schist, and iron-formation, all interbedded; and (3) nongraphitic slate, argillite, and metasiltstone. The second of these units is lithologically like the Glen Township Formation in the Moose Lake-Glen Township panel immediately to the southeast, and is coextensive with the Randall Formation at its type locality (Morey, 1978).

Most of the iron-formation within the panel occurs in map unit (2), as described above, in close stratigraphic association with mafic to intermediate volcanic rocks and graphitic slate. Its distribution is reasonably well known, particularly in the area south of the Mississippi River (Morey and Morey, 1986), where there was much exploration for iron ore in the early part of the twentieth century. The objective of that exploration was to find high-grade "direct-shipping" ore, and the most commonly followed exploration strategy was to seek the nonmagnetic breaks or gaps in elongate positive magnetic anomalies that had been defined by dip-needle surveys. The expectation was that the iron-formations were more or less continuous layers and that the nonmagnetic gaps were places where a normally magnetic iron-formation had been oxidized and leached, and in the process converted from a magnetite-iron silicate rock into one enriched in hematite and depleted in silica. The drilling record shows that these inferences were incorrect in many situations. Lateral facies changes in unenriched iron-formation (i.e., changes from oxide to carbonate or sulfide facies) are responsible for many of the nonmagnetic gaps, and the lateral thinning and stratigraphic pinching out of iron-formation lenses are responsible for even more. The rather large number of places where iron-formation lenses terminate within a stratigraphic sequence of green metavolcanic rocks and black carbonaceous slate (Morey and Morey, 1986) suggests to us that the deposition of iron-formation was closely allied with volcanic activity and was controlled by geochemical and sedimentological factors that were specific to small basins of accumulation. In some respects the stratigraphic setting resembles that of the so-called Algoma-type iron-formations more than that of the classic Superior type (Gross, 1973).

It is clear from the distribution of iron-formation lenses and layers, as well as from the aeromagnetic patterns, that the structure of the South range panel is dominated by elongate, east-northeast-trending folds. In contrast to the Moose Lake-Glen Township panel, the major northeast-trending folds of the South range panel seem not to have been refolded on a major scale. The aeromagnetic trends are linear or curvilinear, not sharply curved as in the terrane immediately to the southeast. However, there is clear evidence for local refolding, as in the vicinity of Deerwood, where crescentic patterns in folded iron-formation are suggestive of type 2 or transitional type 2-3 interference patterns (Ramsay, 1967), and in the local presence of more than one generation of cleavage in some drill cores of schistose or slaty rocks.

The southeastern boundary of the panel is inferred to be a zone of thrust-faulting localized within a narrow, seemingly continuous belt of graphite-rich phyllite and schist that curves gently along the strike of the fold-and-thrust belt for most of its length (Plate 1). The boundary separates two areas of contrasting fold geometry, as discussed above, and is localized within a weak, deformable rock type that is likely to have been a favorable zone for major shear failure during tectogenesis.

The areas of the South range panel mapped as metabasalt and metapelite on Plate 1 are much less well defined than the areas containing the tripartite assemblage of metavolcanic rocks + graphite schist + iron-formation. Areas of metabasalt and metapelite are characterized by nearly identical aeromagnetic patterns consisting of relatively open, low-amplitude, low-gradient anomalies. Drilling data are sparse, but in a very general way they imply that the largest folds in the panel involve the rock sequence metabasalt – tripartite assemblage – metapelite, either in stratigraphic or inverted order of age.

The largest area of pelitic metasedimentary rocks in the panel lies on the northern side of the iron-formation belt that passes through Aitkin and just south of Deerwood (Plate 1). The contact between pelitic rocks and iron-formation in this region is gradational and generally south-dipping, indicating that the pelitic rocks are the structurally lower unit. The temporal order is unknown, however, owing to the lack of stratigraphic top indicators in these very fine grained rocks.

The largest area of metabasalt occupies the core of a long fold in the southern part of the panel. Drilling data are very scarce in the core of the fold, and the lithic variety within the metabasalt unit is probably much greater than the mapping portrays. Both limbs of the fold dip generally to the southeast, and therefore it is regionally overturned to the northwest. Neither structural nor stratigraphic control are adequate to determine whether the fold is antiformal or synformal, however.

**Detailed Description of the Cuyuna North Range Panel**

The northernmost panel of the fold-and-thrust belt is centered on the former iron-mining towns of Crosby and Ironton and extends along a northeast trend about 55 km long. It includes the main mining area of the Cuyuna district. The dominant structural element within this panel is a major synclinorium that involves weakly metamorphosed sedimentary rocks. Its general characteristics were discussed in the broader context of the framework of the fold-and-thrust belt and will not be repeated here.

A key stratigraphic unit in interpreting the geology of the Cuyuna North range panel is the Mahnomen Formation (Schmidt, 1963; Marsden, 1972; Morey, 1978). The Mahnomen has been described as containing chiefly argillite and siltstone in the lower part, and those rocks together with quartzite and limestone in the upper part. Its lower contact has not been penetrated anywhere by drilling, and therefore the thickness of the formation, the exact meaning of "upper" and "lower" parts, and the nature of the subjacent rocks are all matters of interpretation. Its upper contact with a laterally continuous iron-formation (the Trommald Formation of Schmidt, 1963) is relatively abrupt in most places, and has been well described in the main mining district near Crosby and Ironton (Schmidt, 1963; Marsden, 1972).

On the basis of aeromagnetic data and very sparse drilling northwest of Crosby and Ironton district, we have divided the Mahnomen into an upper, more magnetic member and a lower, less magnetic member. The map widths of these units are on the order of 2-3 km, implying stratigraphic thicknesses of roughly half that amount (assuming regional dip is in the 30-45° range). The upper member contains beds of ferruginous argillite and lean iron-formation interlayered with nonferruginous argillite, siltstone, and quartzose sandstone, whereas the lower member lacks the ferruginous components except near its inferred base.

The lower member of the Mahnomen rests with apparent low-angle unconformity on an older sequence of low-grade metasedimentary and metavolcanic rocks derived from various kinds of argillite, lithic graywacke, arkose, quartzite, basalt, intermediate to felsic tuff and tuff-breccia, and, locally, magnetite-chert iron-formation and dolomite. Lithologically this sequence beneath the Mahnomen resembles the Denham Formation in many respects, and, like the Denham, it rests unconformably on Archean basement. All of the sub-Mahnomen section except for the dolomite was mapped as Mille Lacs Group, undivided, by Morey and others (1981). The dolomite unit is the Trout Lake Formation of Marsden (1972), which occupies roughly the same position with respect to the unconformity on Archean basement as does the dolomitic upper member of the Denham Formation with respect to the Archean core of the McGrath gneiss dome.

The metasedimentary rocks associated with iron-formation near Philbrook, in northeastern Morrison County, are part of this enigmatic "basal Mille Lacs Group" sequence (Boerboom, 1987). At Philbrook, these rocks rest on Archean basement and are overlapped unconformably by argillaceous rocks of the Animikie Group in the Long Prairie basin, without an intervening section of Mahnomen Formation. The reason for the disappearance of the Mahnomen between the east and west sides of the Long Prairie basin is not known; however, it may be related to normal faulting beneath the basin that occurred prior to deposition of Animikie Group rocks.

The Mahnomen Formation is conformably overlain by the iron-rich Trommald Formation (Schmidt, 1963), the unit of greatest economic importance in the Cuyuna district. The Trommald is overlain in turn by the Rabbit Lake Formation, or, more specifically, by the lower member of the Rabbit Lake Formation as defined by Marsden (1972). The lower member of the Rabbit Lake consists chiefly of carbonaceous argillite and slate, together with minor interbeds of volcanic rocks and a few lenses of ferruginous chert (Schmidt, 1963). These rocks pass upward into a second major iron-formation layer that is overlain in turn by slate, argillite, graphitic slate, graywacke, and local cherty iron-formation of the upper member of the Rabbit Lake Formation. The rocks of the upper member are limited to the cores of closed synclines in the keel region of the North range synclinorium. The iron-formation unit within the Rabbit Lake sequence is an important marker bed in the Cuyuna district. It formerly was designated as the Emily Member of the Rabbit Lake and was correlated with the intermediate iron-formation layer in the Emily district (Morey, 1978). However, as discussed above, we now conclude that the iron-formations of the Emily district unconformably overlie those of the Cuyuna district, and the iron-formation within the Rabbit Lake sequence therefore cannot be stratigraphically equivalent to rocks in the Emily area.

The stratigraphic succession consisting of the Mahnomen Formation at the base, the Trommald Formation, and the Rabbit Lake Formation at the top is well established. We propose that it be designated informally as the North range group (small g), with the understanding that formal naming may be justified at a later time.

## TECTONIC TIMING

The validity of tectonic models is critically dependent on a proper demonstration of the timing of events. If the western end of the Penokean orogen does in fact consist of a foredeep together with its causative fold-and-thrust belt, as we propose, then the rocks of the fold-and-thrust belt (South range of the Cuyuna district and environs) should be older than the rocks of the foredeep (Nimrod outlier plus Animikie and Long Prairie basins). In this section we review evidence bearing on this question.

Perhaps the most convincing geologic evidence favoring an older age for the rocks of the fold-and-thrust belt is the unconformable truncation of Cuyuna-district structural trends at the base of the Animikie sequence inferred from geophysical maps and computer modeling of geophysical data. This has been discussed at some length in previous sections. In addition, we reemphasize the presence of Cuyuna-district clasts in an Animikie-equivalent paraconglomerate at the southeastern margin of the Long Prairie basin, as well as the regional southeastward thickening and coarsening of graywacke beds in the Virginia and Thomson Formations. The first of these clearly implies that rocks of the Cuyuna district were present in the source terrane during deposition of the Animikie Group, whereas the second is consistent with increasing proximity to a southeastern sediment source. We further point out that the coarser grained graywacke beds in the Thomson Formation contain small but persistent modal fractions of coarse detrital muscovite and lithic clasts of muscovite- and chlorite-bearing phyllite. Coarse muscovite is abundant in the pelitic and semipelitic schists of the Denham and Moose Lake areas (units Pms and Pps of Plate 1), and phyllitic rocks of muscovite and chloritic composition are widely present in the vicinity of Barnum and Kettle River (unit Pgvi, primarily), both within the fold-and-thrust belt. Thus we interpret the presence of these materials in graywacke beds near the southern edge of the main bowl of the Animikie basin as consistent with a southern source, and not necessarily indicative of derivation from a northern terrane of Archean greenstone (cf. Morey and Ojakangas, 1970). The rocks of the Virginia Formation that were deposited along the cratonic margin of the basin are likely to have been derived from Archean greenstone-granite sources, however. In this connection, Peterman (1966) concluded on the basis of initial $Sr^{87}/Sr^{86}$ ratios that the Mahnomen Formation probably was derived from a southern source that contained rocks of mixed Archean age having higher than average Rb/Sr ratios. Such Archean rocks occur within the McGrath-Little Falls panel of the fold-and-thrust belt, and also in the cratonic foreland south of the Great Lakes tectonic zone. Finally, we note again that the rocks of the fold-and-thrust belt show widespread evidence of a recumbent style of folding (Holst, 1982, 1984, 1985; Holm, 1986), whereas recumbent structures are restricted to just the southernmost margin of the Animikie basin. This implies that the rocks of the fold-and-thrust belt had been deformed into nappes prior to deposition of most of the Animikie-basin fill, and is consistent with the temporal overlap of sedimentation and deformation along the tectonically active hinterland margin of a migrating foredeep.

Paleocurrent studies in the Thomson Formation near its type locality at Thomson Dam (Morey and Ojakangas, 1970) reveal an east-west component of flow, indicated by the orientations of sole marks on graywacke beds, and a north-to-south component of flow, indicated by the orientations of cross laminations in the fine-grained upper parts of Bouma-C horizons. Although these data appear to contravene the presence of a nearby source terrane on the south, they can be reconciled with it if the depositional basin had the bathymetric form of a deep trench or elongate trough that trended essentially east-west, more or less parallel to the postulated tectonic highland. Density current flow in bathymetric troughs is commonly axial, and we submit that the sole marks trending east-west (or west-east) in the Thomson Formation were produced by axially flowing density currents along the southern margin of the main bowl of the Animikie basin. The south-flowing weak currents implied by the cross-lamination data from the upper parts of Bouma-C sequences were active in the waning stages of density-current events, and may represent a regime that prevailed on the north slope (south-facing) of the postulated bathymetric trough as axial currents weakened and spread. In such a setting, weak currents affecting the deposition of fine sediments toward the end of a density-current event might well have been southward and directly downslope, more or less perpendicular to the principal east-west flow direction of the axially channeled current. This explanation is largely *ad hoc*, of course, and requires testing against sedimentological observations in the field. Such observations should be rigorously corrected for bulk tectonic distortion, which has been substantial in the area (Holst, 1983, 1985), as well as for solid-body rotation during folding.

Direct isotopic evidence pertaining to the age of volcanism in the fold-and-thrust belt is decidedly slim. Unpublished, as yet unrefined Rb-Sr and Nd-Sm studies of metabasalt samples from the Glen Township area yield preliminary age estimates greater than 2150 Ma (W. Beck, written communication, 1986). These are in the same range as the Rb-Sr age of 2120 $\pm$ 67 Ma reported for a

Kenora-Kabetogama dike (Beck and Murthy, 1982). The Animikie Group rests unconformably on erosionally truncated KK dikes, implying that at least the northern part of the basin fill is younger than about 2120 Ma. Thus the available radiometric data do not vitiate the geologically based inference that the rocks of the fold-and-thrust belt are somewhat older than the rocks of the Animikie basin, but they do not provide close constraints on depositional or tectonic timing. It does appear, however, that the volcanic rocks of the fold-and-thrust belt in east-central Minnesota are significantly older than the 1910 $\pm$ 10 Ma volcanic rocks (Hemlock Formation) of Upper Michigan (Van Schmus, 1976; Van Schmus and Bickford, 1981) or the 1870 $\pm$ 25 Ma volcanic terrane of northern Wisconsin (Banks and Rebello, 1969, recalculated; Afifi and others, 1984).

The later stages of tectonic evolution in the Penokean orogen of east-central Minnesota are more reliably dated. Goldich and Fischer (1986) report a U-Pb zircon age of 1982 $\pm$ 5 Ma for a tectonized granite gneiss at Bremen Creek in Pine County, within the core complex of the McGrath Gneiss dome. They interpret the granite gneiss to be an Early Proterozoic pluton that was emplaced into Archean McGrath Gneiss and subsequently deformed; the reported age is inferred to be a crystallization age, although metamorphic disturbance of U-Pb systematics cannot be ruled out. Goldich and Fischer (1986) also report a U-Pb zircon age of 1869 $\pm$ 5 Ma for tonalite gneiss within the Hillman Migmatite from a locality along Bradbury Creek in Mille Lacs County. The U-Pb systematics of this sample indicate crystallization at 1869 Ma and lead loss at about 480 Ma. The 1869 Ma age is consistent with the ages reported by Van Schmus (1980) for syntectonic plutons in Wisconsin, and strongly suggests that the Hillman Migmatite contains a component of leucosomatic material that was emplaced more or less synchronously with the Freedhem, Bradbury Creek, and Pierz intrusions into the Hillman terrane. None of these larger intrusions into the Hillman nor the principal paleosome of the Hillman itself has been dated by precise U-Pb methods.

Post-orogenic plutons such as the Isle and Warman Granites yield U-Pb ages of about 1770 Ma (Spencer and Hanson, 1984). These rocks appear to have been emplaced slightly before an obscure regional event demarked by Rb-Sr studies in the region. Keighin and others (1972) report Rb-Sr ages of 1740 to 1750 Ma from cataclastically deformed McGrath Gneiss, which presumably date the occurrence of brittle to semibrittle shear. They also report a whole-rock Rb-Sr isochron age (recalculated from the data of Peterman, 1966) of 1730 Ma for the Thomson Formation that presumably is a metamorphic age. We speculate that the cessation of compression in the area and the onset of regional uplift and cooling may have occurred within the interval defined by the spread of Rb-Sr ages. If this is correct, the lower age limit for the second generation of folding and cleavage recognized in the fold-and-thrust belt (Holst, 1982, 1984; Southwick, 1987) may have been about 1740 ma. The earlier recumbent folding is not well constrained in time, being bracketed between the poorly known depositional age of deformed volcanic rocks (ca. 2200 Ma??) and the emplacement age of the post-orgenic plutons (1770 Ma). If our basic tectonic model is correct, namely, that the emplacement of thrust masses onto a cratonic margin caused the downbowing of the Animikie foredeep, then some of the recumbent folding may have been as early as 2100 to 2200 Ma. However, it is probable that folding of recumbent style continued over a long period of plate convergence, and it may have culminated around 1870 Ma, the "peak" of the Penokean orogeny (Van Schmus, 1976; Van Schmus and Bickford, 1981).

## TECTONIC IMPLICATIONS OF VOLCANIC ROCKS AND ROCK ASSOCIATIONS

The volcanic rocks in the fold-and-thrust belt and internal parts of the associated foredeep range in composition from basalt to Na-rhyolite and include flows, hypabyssal sills, and a variety of volcaniclastic types. The most abundant rock types, as judged from the available distribution of outcrop and core samples, are basaltic flows and sills. All rocks have been metamorphosed to greenschist grade or higher, and most are foliated or lineated. Therefore it is likely that their contents of Ca, Na, K, and the large-ion, lithophile trace elements have been modified from original igneous values by metamorphic processes.

Volcanic rocks of both tholeiitic and calc-alkalic composition are represented in the fold-and-thrust belt, but the calc-alkalic suite is less abundant (Fig. 5). When plotted in the $Al_2O_3$-FeO-MgO discrimination diagram of Pearce and others (1977), the data for basaltic rocks scatter widely across several tectonic fields but largely avoid the "orogenic" field (Fig. 6). Similarly, the Zr and Y data are spread widely over the Zr/Y vs Zr diagram of Pearce and Norry (1979) and define neither unique source composition, differentiation trends, nor tectonic environment (Fig.7). The field of island-arc basalt on this diagram is essentially unpopulated, however. Although these diagrams are not definitive, owing to the incomplete distribution of samples, the metamorphosed condition of the rocks, and the inherent imprecision of discrimination plots, two generalizations appear to be warranted. First, calc-alkalic, orogenic, or island-arc compositions are greatly in the minority, and therefore island-arc assemblages probably were not significant constituents of the tectonic mass now represented by the fold-and-thrust belt. Secondly, most of the basaltic rocks have a "within-plate" or continental affinity, which indicates that continental crust played a role in determining their composition.

Rare-earth-element (REE) plots of the Penokean

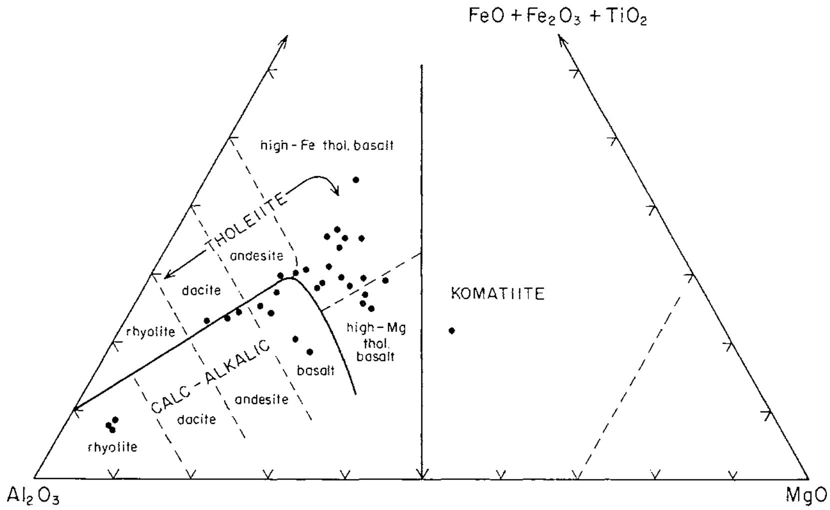


Figure 5. Jensen plot (Jensen, 1976) of volcanic rock compositions from various parts of the fold-and-thrust belt. Includes metamorphosed lavas, hypabyssal intrusions, and fragmented volcaniclastic rocks ranging from 45 to 72 wt% of $SiO_2$.

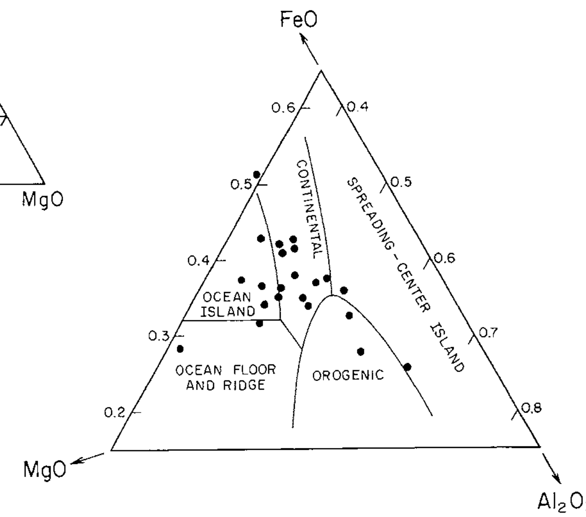


Figure 6. FeO*—MgO—$Al_2O_3$ plot of Pearce and others (1977) showing distribution of basaltic rock compositions from the fold-and-thrust belt. Data are in weight percent. Note the sparsity of points in the orogenic field.

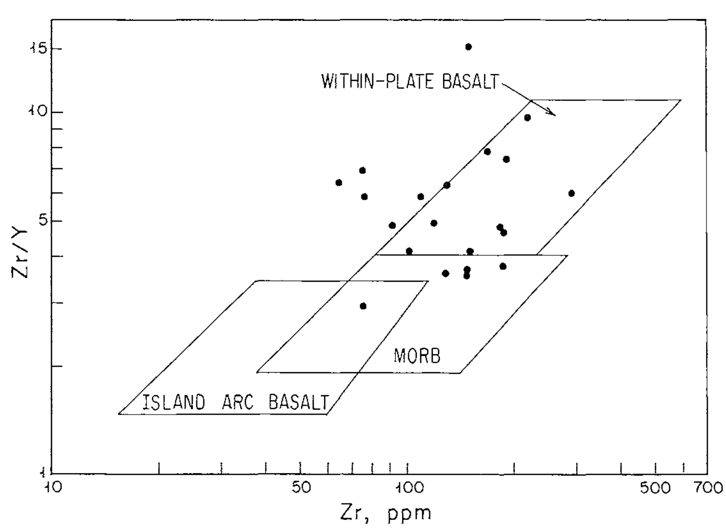


Figure 7. Zr/Y vs Zr diagram from Pearce and Norry (1979) showing distribution of basaltic rock compositions from the fold-and-thrust belt. Note the virtual absence of points from the island arc field.

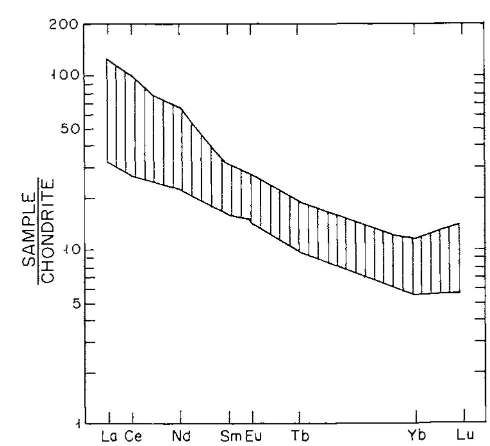


Figure 8. Chondrite-normalized rare-earth element plots for basaltic rocks of the fold-and-thrust belt. Includes unpublished data provided by K.J. Schulz of the U.S. Geological Survey.

basaltic rocks in east-central Minnesota (Fig. 8) are nearly linear and smoothly sloped from light-element abundances of 30-100 x chondrite to heavy-element abundances of about 10 x chondrite. There is virtually no Eu anomaly. Such patterns of moderate REE fractionation are not particularly diagnostic of tectonic setting, although the light REE enrichment factors are higher than those for most oceanic basalts and are consistent with the observed range of values for continental tholeiites (Dupuy and Dostal, 1984). Similar fractionated REE patterns also are characteristic of the more evolved calc-alkalic andesites of island arcs, however (Ringwood, 1977).

The Penokean basaltic rocks are closely associated with quartzose to arkosic arenites and quartz-rich wackes in the Denham Formation (Morey, 1978), in the undivided lower part of the Mille Lacs Group near Philbrook (Boerboom, 1987), and in or adjacent to the Dam Lake quartzite northeast of Mille Lacs Lake. They also are associated with euxinic black shale, chert, iron-formation, and assorted argillaceous to silty mudrocks at various places in the medial panels of the fold-and-thrust belt. These rock associations have been interpreted elsewhere as indicative of deposition in an extensional environment, possibly within local rift basins and on the platforms between rift basins that developed along a foundering continental margin (Larue, 1981, 1983; Morey, 1983).

Another possibility suggested by the volcanic-sedimentary rock associations and the basalt geochemistry is that the medial panels contain the deformed contents of a former marginal (or back-arc) basin. For example, the Early Cretaceous marginal basin in the Andes of Tierra del Fuego lay between the stable craton of southernmost South America and an andesitic arc, and received sedimentary fill from both sides. The sediment received from the cratonic side consisted of quartz-rich wackes, whereas that received from the arc side consisted of lithic wackes rich in volcanic detritus (Dalziel and others, 1975). The markedly quartzose rocks of the continental flank appear to have passed basinward into a thick pile of shale that contained abundant quantities of chert in its lower parts (Saunders and others, 1979). These rocks and the time-equivalent volcaniclastic materials on the arc side of the basin are interpreted to have been deposited on ophiolitic basin floor that contained disrupted continental inliers (Dalziel and others, 1975; Saunders and others, 1979), and the entire assemblage was deformed by cratonward subduction in Middle Cretaceous time (Bruhn and Dalziel, 1977; Bruhn, 1979). Craton-verging nappe structures and thrust faults developed in the supracrustal rocks of the basin fill, supracrustal rocks were detached from ophiolitic basin floor, cratonic basement rocks were intensely reactivated in places where continental inliers lay within ophiolitic crust, and consequently a foreland-style tectonic basin developed on the cratonic side (Fig. 9). The great Patagonian batholith occupies the site of the Cretaceous island arc.

The tectonic evolution of southernmost South America in the latest Mesozoic may have been broadly similar to that of the Penokean orogen of the Lake Superior region in the Early Proterozoic. Parts A and B of Figure 10 are schematic interpretations of the Mesozoic analog that have been taken with slight modification from Bruhn and Dalziel (1977). In the case of the Penokean orogen, the fold-and-thrust belt may consist chiefly of the sedimentary and volcanic fill of a marginal basin that subsequently was destroyed by convergence of the flanking arc and craton. Loading of the cratonic crust by the stacked thrusts along the rear side of the closed marginal basin produced a foredeep, now seen in the main bowl of the Animikie basin and the Long Prairie basin and Nimrod outlier. The deep roots of the associated volcanic arc may be manifested in the plutonic rocks (1770-1890 Ma) in the McGrath-Little Falls panel and adjacent areas to the south (Morey, 1978; Morey and others, 1981), and shallower remnants may be represented in the metavolcanic assemblages of the Wisconsin magmatic terrane (Sims, 1987).

## TECTONIC SUMMARY

In our opinion the geological and geophysical evidence clearly indicate that the Penokean orogen in Minnesota consists of a foreland basin and its associated fold-and-thrust belt, and that the cratonic side of the orogen lay on the north and northwest in terms of present directions. Although the orogen developed in response to plate convergence during its later history, the nature of its development prior to collision and closing is far less certain. Two scenarios have been presented (Figs. 2 and 10) that lead to rather similar results, but they differ substantially in their kinematics. In the first, illustrated conceptually in Figure 2, the southern passive margin of the Archean Superior craton was partially subducted beneath a tectonic collage of arcs, accretionary prisms, and continental fragments as an ocean basin was consumed. In the second, diagrammed in Figure 10, a back-arc basin was destroyed by arc-to-craton convergence resulting from ocean-floor subduction in front of the arc. The first of these implies a southeast-dipping subduction zone (present directions) and ultimate development of a suture. The second implies a northwest-dipping subduction zone and the development of an Andes-style continental-margin volcanic arc somewhere to the southeast of the area mapped in this study—perhaps in the Wisconsin magmatic terrane. The geochemical characteristics and lithostratigraphic associations of the volcanic rocks in east-central Minnesota are not particularly arc-like, and the rocks appear more compatible with a back-arc setting than with an arc-trench environment. Therefore we tentatively favor the back-arc scenario based on the southern Chile analog, as diagramed in Figure 10. However, the geochemical, geochronological, and structural data are collectively so sparse and ambiguous that no firm conclusion as to pre-

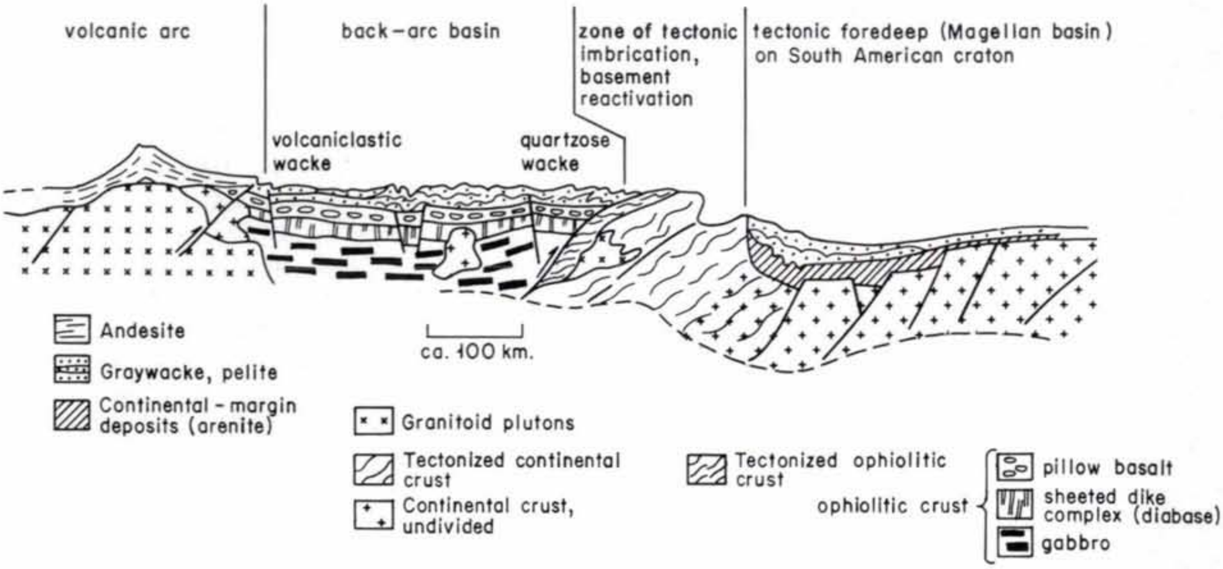


**Figure 9. Schematic cross section showing the inferred regional style of deformation during back-arc basin destruction in the Andes of southern Chile during Early Cretaceous time. Redrawn from Bruhn (1979). The main bowl of the Animikie basin is tectonically analogous to the Magellan basin, and the various panels of the Penokean fold-and-thrust belt may be analogous to the zone of basement reactivation on this diagram.**

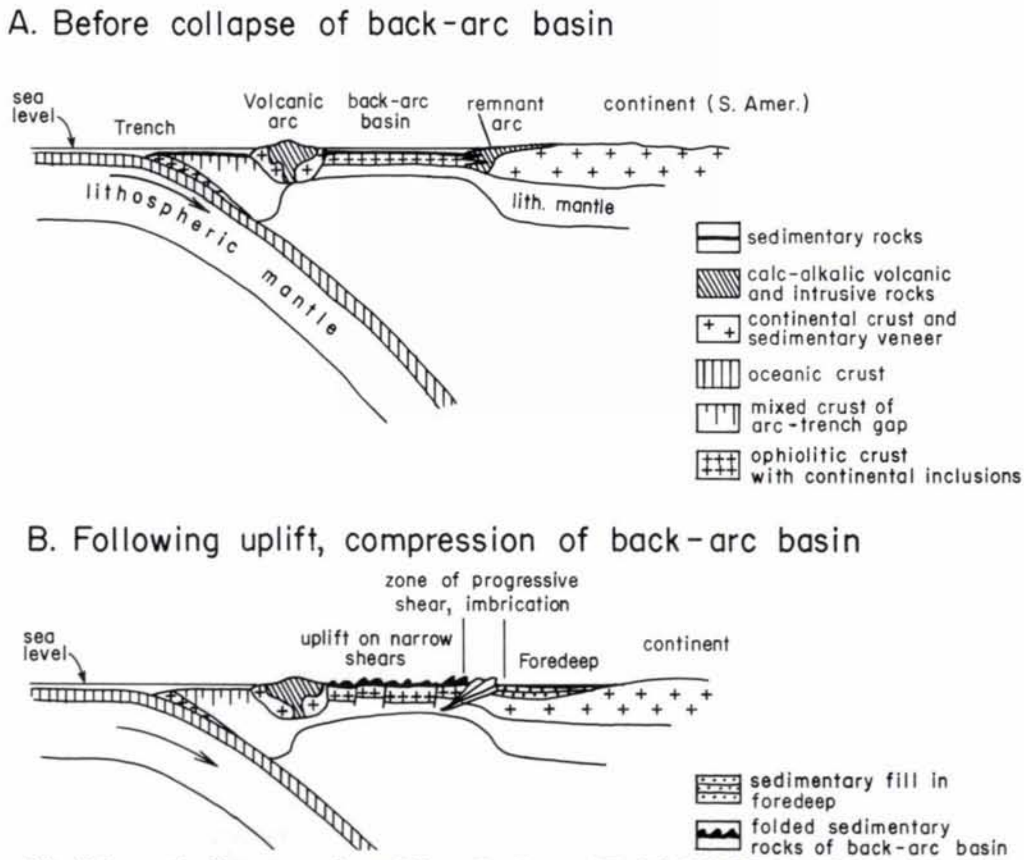


**Figure 10. Schematic diagrams adapted from Bruhn and Dalziel (1977) depicting the tectonic setting of the southern Chile back-arc basin during mid-Mesozoic time. Conditions approximately equivalent to those shown here may have prevailed along the southern margin of the Superior craton in the Early Proterozoic. Remnants of the deformed marginal basin may be preserved in the Penokean fold-and-thrust belt of Minnesota, whereas rocks of the remnant arc may be predominant in the Wisconsin magmatic terrane to the south.**

collisional tectonic setting is possible or advisable at the present time.

## ACKNOWLEDGMENTS

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