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Chapter U

Precambrian Crustal Blocks in Minnesota—Neodymium Isotope Evidence from Basement and Metasedimentary Rocks

By S.R. HEMMING, G.N. HANSON, and S.M. McLENNAN

U.S. GEOLOGICAL SURVEY BULLETIN 1904

CONTRIBUTIONS TO PRECAMBRIAN GEOLOGY OF LAKE SUPERIOR REGION

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

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Precambrian Crustal Blocks in Minnesota—Neodymium Isotope Evidence from Basement and Metasedimentary Rocks

By S.R. Hemming,[1,2] G.N. Hanson,[1] *and* S.M. McLennan[1]

Abstract

A Sm-Nd survey of Precambrian granitic and metasedimentary rocks collected from several geophysically defined blocks in central Minnesota confirms the presence of some fundamental geologic boundaries previously mapped on the basis of structure. The Malmo discontinuity—an Early Proterozoic structure—separates the Archean Minnesota River Valley terranes from an Early Proterozoic (Penokean magmatic) terrane and the McGrath Gneiss dome of east-central Minnesota. North of this boundary, the Penokean fold-and-thrust belt can be divided into fault-bounded terranes that were assembled during the Penokean orogeny. Each terrane within the study area has distinct crust formation ages. These terranes and ages, from south to north, are as follows: (1) Early Proterozoic crust of the Penokean magmatic terrane; (2) McGrath dome and Benson block, including the McGrath Gneiss and Ortonville Granite (T_{DM} (depleted mantle) ages from 3.0 to 3.3 Ga), other granites within the Benson block (T_{DM} of 2.7–2.9 Ga), and metasedimentary rocks of the Mille Lacs Group that overlie the McGrath Gneiss (T_{DM} of 2.6–3.1 Ga); (3) metasedimentary and metavolcanic rocks of the Moose Lake–Glen Township terrane (T_{DM} of 2.1 Ga); (4) metasedimentary rocks of the Cuyuna North range (T_{DM} of 2.5–3.0 Ga); and (5) the main bowl of the Animikie basin, which records a progression from Archean sources in the lower units to Early Proterozoic sources in the younger (and more southerly) units.

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INTRODUCTION

The Great Lakes region of North America lies at the transition from the Archean Superior craton of the Canadian Shield into Early Proterozoic orogenic complexes that form the basement of the midcontinent (Van Schmus, 1976; Nelson and DePaolo, 1985; Sims, 1990). The Penokean and Trans-Hudson orogens, bordering the Superior craton (fig. 1), include large volumes of newly formed Early Proterozoic continental crust (Chauvel and others, 1987; Horan and others, 1987; Spencer, 1987; Barovich and others, 1989). Continuing crustal accretion of the North American continent during latter stages of the Early Proterozoic is recorded in extensive terranes extending from the Central Plains throughout the southwestern United States (Nelson and DePaolo, 1985; Bennett and DePaolo, 1987; McLennan and others, in press).

Minnesota lies astride the boundary between Archean rocks of the Superior province and Early Proterozoic rocks of the Penokean orogen (Sims and others, 1993). The boundary in Minnesota is named the Malmo structural discontinuity (Southwick and others, 1988), and both it and adjacent Archean (Southwick and others, 1989) and Proterozoic rocks (Southwick and others, 1988) are poorly exposed; delineation of tectono-stratigraphic terranes has been based mainly on aeromagnetic and gravity maps combined with selective test-drilling (Southwick and Morey, 1991). Because of the utility of Nd isotope data in delineating structural blocks having different lithologies and histories (Nelson and DePaolo, 1985; Bennett and DePaolo, 1987), a systematic Sm-Nd isotope study was carried out to test and supplement the geologic framework established by the mapping. In general, the Nd data presented here support the earlier conclusions based on

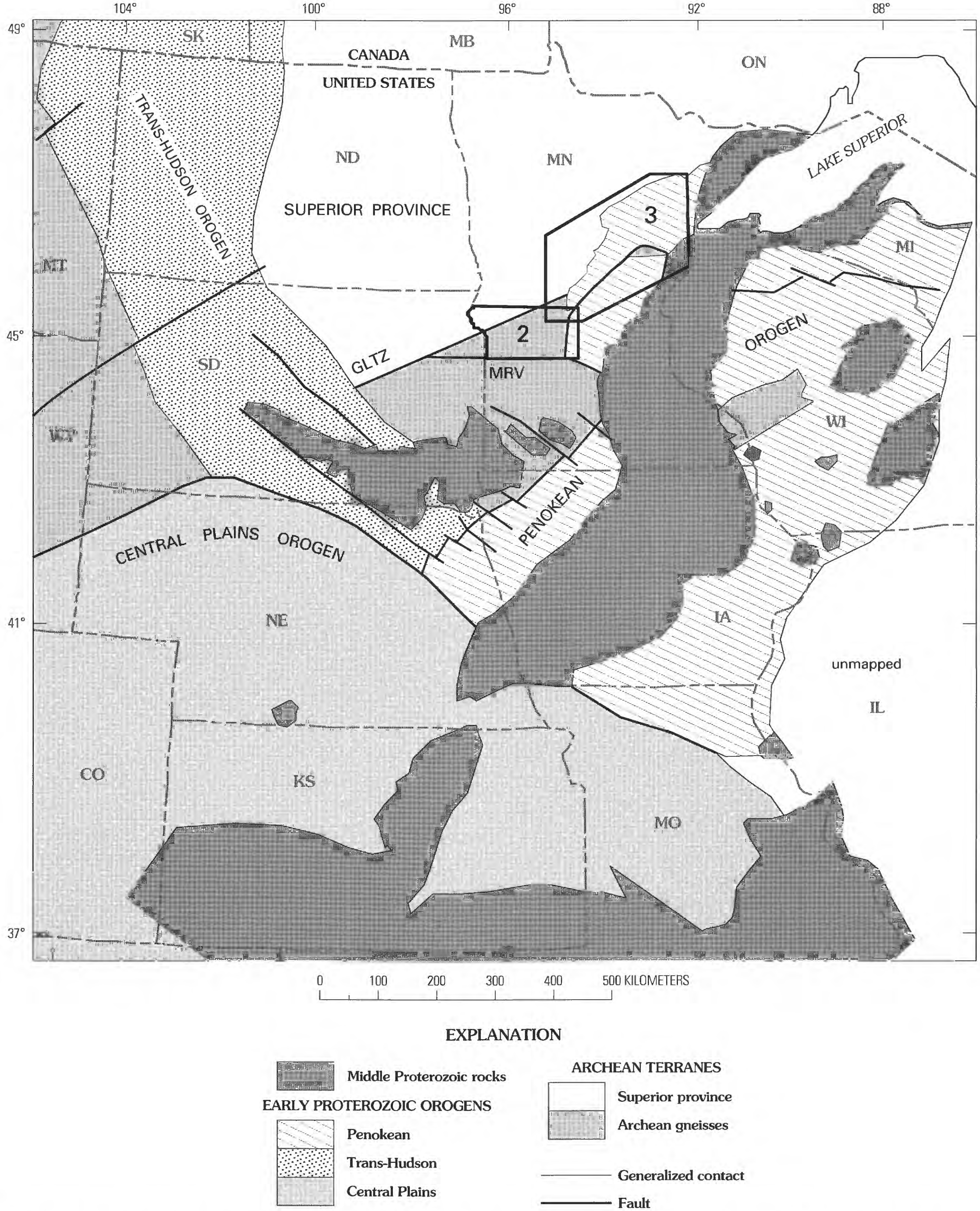

Figure 1. Precambrian basement map of midcontinent region, United States, showing location of Penokean orogen relative to Superior province and Early Proterozoic orogens that make up the midcontinental United States. GLTZ, Great Lakes tectonic zone, is interpreted by Sims and others (1980) to be the boundary between volcano-plutonic complexes of Superior province and older gneiss terranes of Minnesota River Valley (MRV). Modified from Sims and Peterman (1986) and Sims (1990).

mapping, but they also reveal some problems that require additional isotopic studies.

Stratigraphic names of Early Proterozoic strata are used extensively in this report. As a guide to these names the reader is referred to figure 7 in Morey and Van Schmus (1988) and figure 1 in Ojakangas (1994).

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GEOLOGIC SETTING

Superior Province

The Superior province of the Canadian Shield (fig. 1) is interpreted to consist of a series of arc terranes that were accreted from north to south during the interval ≈3.0 to 2.6 Ga (Krogh and Davis, 1971; Card and Ciesielski, 1986; Hoffman, 1989). Morey and Sims (1976) recognized two distinct Archean terranes in Minnesota that differ in age, rock assemblages, metamorphic grade, and structural style. Greenstone-granite terrane (Wawa subprovince, Card, 1990) rocks of the southern Superior province are characterized by mantle-like initial radiogenic isotopic compositions (for example, Shirey and Hanson, 1986; Stern and Hanson, 1992; Gariepy and Allegre, 1985; Arth and Hanson, 1975). In Minnesota, arc-like rocks are inferred to be in contact with mainly older, high grade gneisses of the Minnesota River Valley terranes along the Morris fault (G.B. Morey, oral commun., 1994). Sims and others (1980) and Sims and Day (1993) interpreted the Morris fault to be a segment of the Great Lakes tectonic zone, a major Late Archean crustal boundary between Late Archean greenstone-granite terrane (on the north) and Middle Archean gneiss throughout the Lake Superior and Lake Huron regions. In central Minnesota, the Morris fault segment of the Great Lakes tectonic zone (figs. 1, 2, 3) has been interpreted to be a seismic reflector that dips northward at 30° to mid-crustal level (Gibbs and others, 1984). More recently, it has been suggested that the shallow-dipping reflectors are actually recumbent and gently inclined folds, and the Morris fault has a steep southeast dip that is transparent in seismic profiles (Sims and Day, 1993).

Minnesota River Valley Gneiss Terranes

Recent geophysical work and scientific drilling by the Minnesota Geological Survey (Southwick and others, 1989, 1990; Southwick, 1993) have provided evidence of multiple terranes within the Minnesota River Valley region, and the isotope systematics of the region are complicated. Despite the complexity, gneisses that crop out along the Minnesota River Valley in the vicinity of Morton and Montevideo (fig. 2) are known to have Middle Archean heritage (McCulloch and Wasserburg, 1976; McCulloch, 1980; Goldich and others, 1970) and are interpreted to have experienced high-grade metamorphism and crustal melting in the Late Archean (≈3.0 Ga and ≈2.6 Ga, Goldich and Wooden, 1980). Late Archean high-grade metamorphism and crustal melting (such as in the Sacred Heart Granite, Doe and Delevaux, 1980) in the Minnesota River Valley are attributed to continental collision of the Minnesota River Valley gneisses with the Superior province rocks along the Great Lakes tectonic zone (Sims and others, 1980; Hoffman, 1988) at about 2.68 Ga. Although the ≈1.8 Ga granite of Section 28 has Pb isotopic compositions that suggest it was derived from crustal melting (Doe and Delevaux, 1980), and zircon lower intercept ages in the Morton area are Early Proterozoic (Goldich and Wooden, 1980), Early Proterozoic metamorphism is not generally regarded as profoundly overprinting older metamorphism in this area. (See, among others, Doe and Delevaux, 1980; Goldich and Wooden, 1980.)

Gneisses having a structural fabric similar to that in the Minnesota River Valley crop out sporadically between exposures in the river valley and the trace of the Great Lakes tectonic zone (Sims and others, 1980). The gneiss terranes are truncated on the east (fig. 2) by the Early Proterozoic Malmo discontinuity (Southwick and Morey, 1991). Some of the gneisses, located east of the Malmo discontinuity in the zone previously considered to be Middle Archean gneisses (Morey and Sims, 1976), have Early Proterozoic Nd depleted mantle model ages (Horan and others, 1987). Thus, the extent of Archean crust in this region is uncertain.

Within the Minnesota River Valley gneiss terranes (fig. 2), south of the Great Lakes tectonic zone, are several tectonic blocks that have been identified on the basis of geophysical lineaments and geologic mapping (Southwick and others, 1989). From north to south, these are (Southwick and others, 1989, 1990; Southwick, 1993):

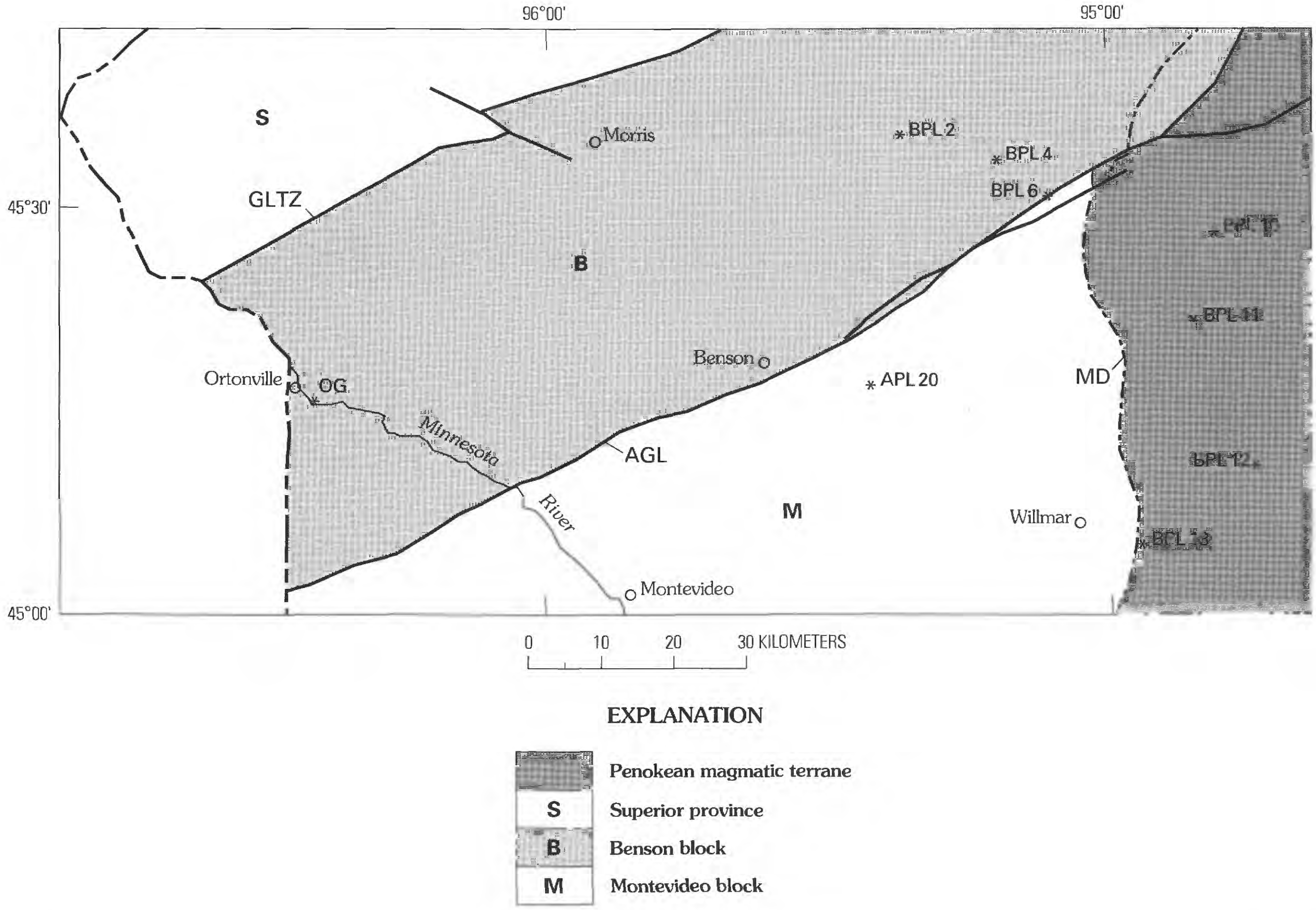

Figure 2. Precambrian rocks in a part of western Minnesota. GLTZ, Great Lakes tectonic zone (Sims and others, 1980). AGL, Appleton geophysical lineament (Southwick and others, 1989). MD, Malmo discontinuity (Southwick and Morey, 1991). Sample localities are marked with asterisks; cores (BPL and APL designations) are from the Minnesota Geological Survey test-drilling program, and sample localities are from Southwick and others (1990). OG, Ortonville Granite. Modified from Southwick and others (1990).

(1) Benson block, (2) Montevideo block, (3) Morton block, and (4) Jeffers block (D.L. Southwick, written commun., 1994). The Morton and Jeffers blocks are south of the area of figure 2. The Benson block (fig. 2) is a poorly exposed terrane composed of gneiss and abundant granite. The Appleton geophysical lineament (fig. 2) separates it from the Montevideo block, which is composed primarily of gneissic rocks such as those exposed along the Minnesota River Valley from Sacred Heart to Granite Falls (≈15 km south of the area of fig. 2). The rock types in the Benson block are sufficiently different from those in the Montevideo and Morton blocks (Goldich and others, 1970, among others) for Southwick and others (1989) to question whether the ≈3.5 Ga age component and the granulite facies metamorphism are represented in the Benson block. Our results do not unambiguously resolve this question, although we have found no depleted mantle model ages greater than 3.1 Ga in the Benson block.

Early Proterozoic Geology

The Early Proterozoic Penokean orogen (fig. 1) is a northwest-verging tectonic system along the south margin of the Superior craton that is exposed in Minnesota, Wisconsin, and Michigan (Goldich and others, 1961; Cannon, 1973; Sims and Peterman, 1983), and may have extended to the east beyond the Grenville front of Ontario (Dickin and McNutt, 1989, among others). The Penokean orogen is interpreted to consist of a deformed continental margin prism and associated foreland basin, the Animikie basin, overlying an Archean craton (fig. 3) (Hoffman, 1987, 1988; Southwick and others, 1988), and a southeastern assemblage of arc terranes, termed the Wisconsin magmatic terranes (Sims, 1987). Two terranes with extensive Early Proterozoic magmatism have been identified in Wisconsin (LaBerge and Myers, 1984; Sims and others, 1989; Brown and Maass, 1992; Maass and Brown, 1993): the

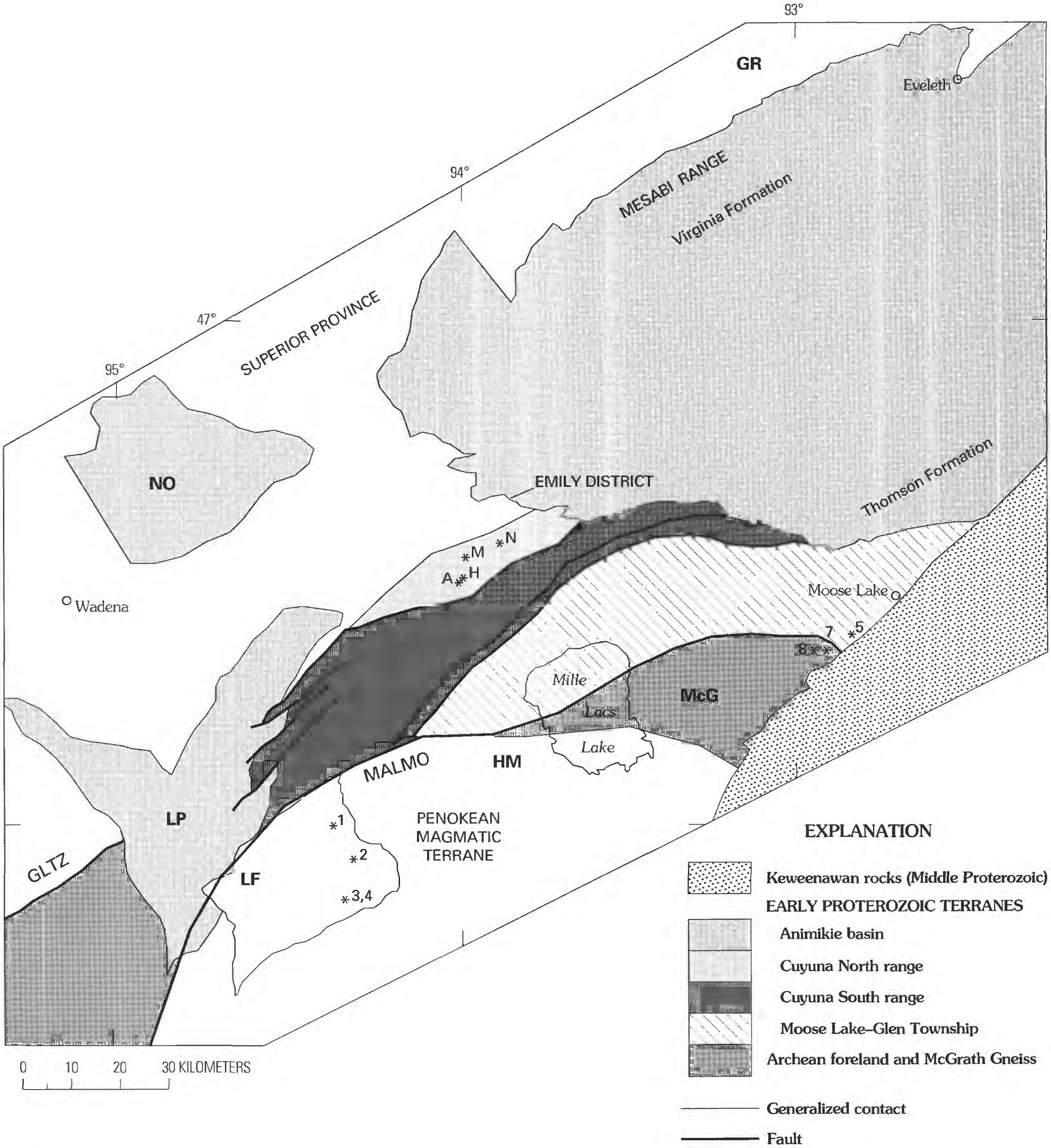

Figure 3. Map of Penokean orogen in central Minnesota. GLTZ, Great Lakes tectonic zone (Sims and others, 1980); MALMO, Malmo discontinuity; GR, Giants Range Granite. Within the North range of the Cuyuna district, A, H, M, and N represent Arko, Hillcrest, Merrit, and Northland cores, respectively (Grout and Wolf, 1955). LF, McG, HM, LP, NO represent Little Falls Formation, McGrath Gneiss, Hillman Migmatite, Long Prairie basin, and Nimrod outlier, respectively. The numbers are SRH sample designations in tables 1 and 2. Modified from Southwick and others (1988).

Pembine-Wausau terrane in the north and the Marshfield terrane in the south (Sims and others, 1989).

Within the continental margin prism in Wisconsin and Michigan, Barovich and others (1989) found that the Nd isotopic character of the lower stratigraphic units of the Marquette Range Supergroup is consistent with derivation from Late Archean sources in the Superior province. However, the Nd isotope character of Michigamme Formation, the uppermost unit of the Marquette Range Supergroup, is more complicated. Samples in the northern part of Barovich and others' study area, near exposed Archean basement, have Late Archean sources and lack evidence for an Early Proterozoic contribution (T_{DM} (depleted mantle age) = 2.70–3.11 Ga), whereas samples in the southern part have more primitive Nd isotopic characteristics (T_{DM}=2.04–2.29 Ga), comparable to those of the Wisconsin magmatic terranes.

In central Minnesota, the rocks of the Early Proterozoic sedimentary and volcanic prism are metamorphosed and strongly folded and faulted (Southwick and others, 1988; Southwick and Morey, 1991). Rocks assigned to the Mille Lacs Group occur within the Penokean fold-and-thrust belt where they have been tectonically dismembered into several slices that are bounded by structural discontinuities, and they probably do not represent a coherent stratigraphic package (Southwick and others, 1988). Southwick and others (1988) divided the fold-and-thrust belt into three parts (fig. 3): (1) external zone, North range of Cuyuna district and Thomson Formation outcrops; (2) medial zone, South range of Cuyuna district and Moose Lake–Glen Township terrane; and (3) internal zone, McGrath–Little Falls terrane.

Within the external zone, the North range of the Cuyuna district consists of the Mille Lacs Group overlain by the North Range Group (Schmidt, 1963). The Mille Lacs Group consists of quartz-rich 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 (Morey, 1978). The North Range Group (Morey and Southwick, 1993) consists, in ascending order, of (1) the Mahnomen Formation, a quartz-rich sandstone-siltstone sequence; (2) the Trommald Formation, an iron-rich and locally manganese rich sequence; and (3) the Rabbit Lake Formation, a black shale–graywacke sequence.

The medial zone of the fold-and-thrust belt is composed dominantly of volcanic and related rocks of the Mille Lacs Group, although some unnamed fine-grained sedimentary sequences exist in the structurally higher zones (Southwick and Morey, 1991; Morey and Southwick, 1993). Beck (1987) determined a whole-rock Sm-Nd isochron age of 2,197±39 Ma for the Glen Township Formation basalts of the Mille Lacs Group. Furthermore, the Nd isotopic composition of these basalts (ε_{Nd}(2.2 Ga)=+2.8) is consistent with derivation from a depleted mantle source at that time.

The internal zone or McGrath–Little Falls terrane is composed of several types of gneisses, amphibolite-facies metasedimentary schist, and a variety of granitoid intrusions (Southwick and others, 1988). Spencer (1987) and Horan and others (1987) concluded that the Early Proterozoic granitoid intrusions and the spatially associated Early Proterozoic mafic dikes of this belt near St. Cloud are products of an arc system. Nd and Pb isotopic compositions are identical within both mafic and granitic rocks in the St. Cloud area and indicate a substantial Early Proterozoic mantle contribution (Horan and others, 1987; Spencer, 1987). It is likely that any extensive volcano-plutonic arc terrane equivalent to the Wisconsin magmatic terranes was mostly displaced by the Middle Proterozoic Midcontinent rift into southeastern Iowa (fig. 1).

Although rocks of the Animikie Group are deformed in the southern part of the Animikie basin, they lie with angular unconformity on the older sequences of the fold-and-thrust belt (Southwick and others, 1988; Southwick and Morey, 1991; Morey and Southwick, 1993). Southwick and others (1988) and Southwick and Morey (1991) interpreted the Animikie basin of central Minnesota to be a foreland basin to the Penokean orogen, in which case the uppermost units are flysch deposits derived from the south. Hemming and others (1992; 1995) found that the Thomson and Virginia Formations (uppermost Animikie Group, fig. 3) have primitive Nd isotopic ratios consistent with their having been derived solely from Early Proterozoic sources similar to the Wisconsin magmatic terranes. The Rove Formation of the Gunflint Range, near the northeastern Minnesota-Ontario border, thought to be stratigraphically equivalent to the Virginia Formation (Morey, 1967, among others), has Nd model ages of 2.0–2.6, suggesting mixing of Archean and Early Proterozoic sources (Hemming and others, 1995).

SAMPLE SELECTION AND ANALYSIS

Our samples fall into three groups: (1) basement plutons and gneissic plutons of the Archean foreland (figs. 2 and 3) and McGrath–Little Falls terrane (fig. 3); (2) pre-Animikie Group metasedimentary rocks of the fold-and-thrust belt (figs. 2 and 3); and (3) plutons east of the Malmo discontinuity (fig. 2) (Southwick and others, 1990).

Analytical Data

Approximately 20 g of each rock was powdered in an agate shatter box; 200 mg of this powder was fused with a lithium metaborate flux at 1,200°C for 10 minutes and dissolved in 30 mL of 1N HNO_3. Five mL aliquots were spiked with a mixed REE (rare earth element) spike. Rare earth elements were separated as a group on columns with 50WX8 cation exchange resin, with elution by HCl followed by HNO_3. The rare earth elements were then separated into smaller groups on 50WX8 cation exchange columns using methylactic acid (see Stern and Hanson, 1991). For concentration data, Sm and Nd were collected and analyzed together on a double, degassed Re filament assembly by isotope dilution on an NBS design 15 cm

Table 1. Nd isotopic data from igneous and metaigneous rocks in central and western Minnesota

[$\varepsilon_{Nd}(T)$ represents deviation in parts per 10^4 of the $^{143}Nd/^{144}Nd$ ratio from average chondritic meteorites at any specific time T (here, in billions of years). $f_{Sm/Nd}$ represents fractional deviation of the $^{147}Sm/^{144}Nd$ ratio from average chondritic meteorites. T_{DM}, depleted mantle age. Depleted mantle values from Taylor and McLennan (1985). Basement cores are described in Southwick and others (1990). Giants Range Granite sample from Arth and Hanson (1975). Blank, no data]

Sample No.	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\varepsilon_{Nd}0$	$\varepsilon_{Nd}1.8$	T_{DM} (Ga)	$f_{Sm/Nd}$
Depleted mantle			0.2170	0.510696	10.0	5.3		0.103
Basement cores								
BPL 2a	18.6	138	0.0813	0.510696	-37.9	-11.3	2.74	-0.587
BPL 2b	3.79	36.4	0.0629	0.510312	-45.4	-14.5	2.79	-0.680
BPL 4a	17.0	9.01	0.1135	0.511220	-27.7	-8.5	2.83	-0.423
BPL 4b	4.83	22.8	0.1283	0.511439	-23.4	-7.6	2.92	-0.348
BPL 6				0.512675	0.7			
BPL 11	18.5	130	0.0863	0.511182	-28.4	-2.9	2.28	-0.561
BPL 12	1.72	45.2	0.0936	0.511212	-27.8	-4.0	2.38	-0.524
BPL 13	1.88	12.2	0.0932	0.510751	-36.8	-13.0	2.93	-0.526
APL 20-343	2.33	12.6	0.1119	0.511331	-25.5	-5.9	2.62	-0.431
Ortonville Granite								
OG 14b	1.40	11.1	0.0768	0.510363	-44.4	-16.8	3.01	-0.610
OG 11b	4.87	43.8	0.0672	0.510141	-48.7	-18.9	3.04	-0.659
OB 37	6.57	38.6	0.1028	0.510794	-36.0	-14.4	3.12	-0.477
McGrath Gneiss								
SRH 7d	2.71	18.4	0.0891	0.510520	-41.3	-16.5	3.11	-0.547
SRH 8	3.83	16.8	0.1376	0.511423	-23.7	-10.1	3.29	-0.300
SRH 8b	5.71	34.0	0.1014	0.510741	-37.0	-15.1	3.15	-0.484
Giants Range Granite								
DL 7	4.28	32.5	0.0796	0.510612	-39.5	-12.5	2.80	-0.595

radius-of-curvature mass spectrometer. For isotopic composition, Nd was completely separated from Sm and Ce. Nd isotopic composition was measured in static mode on a Finnigan MAT 262 using a degassed double Re filament assembly. Samples were corrected assuming linear mass fractionation and $^{146}Nd/^{144}Nd=0.7219$, and accepted runs had in-run precision better than ±0.000010 (2 sigma mean). Nd isotopic data were accepted only if the measured $^{148}Nd/^{144}Nd$ was in the range 0.241620±0.000020. The external reproducibility of Nd standard solutions using this filter is better than 0.3 epsilon units. During data collection for this study, less than 5 percent of measurements failed to meet this criterion. The average $^{143}Nd/^{144}Nd$ value measured for La Jolla Nd standard solution was 0.511820 during the period of these analyses, and the ratios were adjusted to a value of 0.511865.

Results

Results from plutonic rocks are presented in table 1, and results from metasedimentary rocks are presented in table 2. Plots of $f_{Sm/Nd}$ versus ε_{Nd}(time) (Shirey and Hanson, 1986) allow an evaluation of Nd isotope systematics at a given time that makes it conceptually simple to compare data from different REE reservoirs.

Table 2. Nd isotopic data from Early Proterozoic metasedimentary rocks in central Minnesota

[$\varepsilon_{Nd}(T)$ represents deviation in parts per 10^4 of the $^{143}Nd/^{144}Nd$ ratio from average chondritic meteorites at any specific time T (here, in billions of years). $f_{Sm/Nd}$ represents fractional deviation of the $^{147}Sm/^{144}Nd$ ratio from average chondritic meteorites. T_{DM}, depleted mantle age]

Sample No.[1]	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\varepsilon_{Nd}0$	$\varepsilon_{Nd}1.8$	T_{DM} (Ga)	$f_{Sm/Nd}$
Thomson Formation								
Sandstone	4.53	24.4	0.1139	0.511679	-18.7	0.4	2.17	-0.42
Shale	5.02	25.5	0.1191	0.511768	-17.0	1.0	2.14	-0.39
North Range Group								
Rabbit Lake Formation:								
Hillcrest 80.2	2.03	11.7	0.1052	0.511005	-31.9	-10.8	2.91	-0.465
Hillcrest 136.7	1.20	5.74	0.1262	0.511339	-25.3	-9.1	3.02	-0.358
Hillcrest 140.7	3.50	21.8	0.0970	0.510913	-33.6	-10.7	2.82	-0.507
Arko box 150	3.24	18.8	0.1042	0.511332	-25.5	-4.1	2.45	-0.470
Mahnomen Formation:								
Merrit 718	1.65	9.85	0.1148	0.511315	-25.8	-6.9	2.72	-0.416
Merrit 753.8	1.95	9.69	0.1215	0.511272	-26.6	-9.3	2.98	-0.382
Merrit 771	2.43	12.8	0.1144	0.511134	-29.3	-10.4	2.98	-0.418
Northland 369.4	3.87	25.4	0.0922	0.510924	-33.4	-9.3	2.70	-0.531
Northland 774.8	2.79	15.9	0.1060	0.511228	-27.5	-6.6	2.62	-0.461
Mille Lacs Group								
Little Falls Formation:								
SRH 1	5.76	29.8	0.1170	0.511744	-17.4	1.0	2.13	-0.405
SRH 1a	5.97	30.0	0.1201	0.511794	-16.5	1.2	2.13	-0.389
SRH 2	5.17	26.7	0.1169	0.511711	-18.1	0.3	2.18	-0.406
SRH 3	2.10	8.29	0.1532	0.511948	-13.5	-3.4	2.85	-0.221
SRH 4b	5.42	27.5	0.1190	0.511769	-17.0	1.0	2.14	-0.395
SRH 4e	5.88	29.0	0.1221	0.511797	-16.4	0.7	2.18	-0.376
BPL 10a[2]	6.16	32.6	0.1143	0.511620	-19.9	-0.8	2.26	-0.419
BPL 10b[2]	4.74	29.0	0.0988	0.511309	-25.9	-3.3	2.36	-0.497
Denham Formation:								
Moose Lake–Glen Township panel								
SRH 5a	7.47	36.4	0.1238	0.511878	-14.8	2.0	2.07	-0.370
McGrath–Little Falls panel								
SRH 7b (amphibolite)	2.38	10.1	0.1429	0.511845	-15.5	-3.1	2.67	-0.273
SRH 7f (quartzite)	1.22	7.51	0.0981	0.510700	-37.8	-15.1	3.12	-0.501
SRH 7j (calc. silicate)	3.04	12.3	0.1494	0.512004	-12.4	-1.4	2.57	-0.241

[1]Numbers after Hillcrest, Merrit, and Northland are depth in feet in cores.

[2]Little Falls(?) Formation BPL samples are described in Southwick and others (1990).

Figure 4 is a schematic $f_{Sm/Nd}$ versus $\varepsilon_{Nd}(T)$ plot to show how different reservoirs and processes plot. Data from central Minnesota are presented in figure 5. Data from different terranes of Southwick and others (1988), Southwick and Morey (1991), Southwick and others (1990), and Morey and Southwick (1993) are presented on separate plots for clarity (fig. 5). Core samples in eastern parts of the Benson block (fig. 5*A*, table 1) have Late Archean Nd model ages. These samples could be juvenile Late Archean granites or they could be Early Proterozoic granites with compositions representing mixing between older Archean crustal sources and newly derived granites such as found east of the Malmo discontinuity. Ortonville Granite samples have a large variation in $f_{Sm/Nd}$ but a small variation in Nd model age (fig. 5*A*, table 1), implying that the Nd model age is a reasonable estimate of the mantle extraction age. For reference and discussion, published data from igneous rocks of the Wisconsin magmatic terranes from Wisconsin and Minnesota (Horan and others, 1987; Spencer, 1987; Barovich and others, 1989) are plotted in figure 5*D*, and data from sedimentary rocks (Miller and O'Nions, 1985; Stille and Clauer, 1986; Jacobsen and Pimentel-Klose, 1988; Barovich and others, 1989; Hemming and others, 1995) of the Animikie basin are plotted in figure 5*F*. One sample of the Rabbit Lake Formation (fig. 5*E*, table 2) has a substantial Early Proterozoic component, opening the possibility that all samples could be mixtures between Early Proterozoic and Archean sources with crustal histories older than the ≈2.9 Ga segments of the Superior province. Regardless, these samples have a large Archean source contribution, and are distinct from nearby upper Animikie Group sedimentary rocks (fig. 5*F*), from most of the Little Falls Formation, and from the Denham Formation sample from the Moose Lake–Glen Township terrane.

DISCUSSION

Archean Foreland

Although the McGrath Gneiss is probably allochthonous, having been transported northward an unknown distance on the south-dipping Malmo structure (fig. 6; written commun. from D.L. Southwick concerning magnetotelluric data from R. Wunderman), it has similar Nd systematics to the Ortonville Granite, and both make up part of the Archean foreland (fig. 5*A*, *B*) on which the Penokean orogen developed (Southwick and others, 1988; D.L. Southwick, written commun., 1994). The Ortonville Granite and BPL cores 2, 4, and 6 are all in the Benson block (fig. 2); however, in its Nd isotopic systematics (fig. 5*A*) the Ortonville Granite, whose T_{DM} values range from 3.0 to 3.1 Ga, is distinct from the other granites, in which T_{DM} ranges from 2.7 to 2.9 Ga.

Although three samples of the Ortonville Granite (fig. 2) and three samples of the McGrath Gneiss (T_{DM} of 3.0–3.3 Ga; table 1) have Nd isotopic compositions that are slightly more evolved than most Superior province rocks (fig. 5*A*), their ε_{Nd} (1.8 Ga) values are not nearly so negative as they would be if they had acquired their light rare earth element enriched character at 3.5 Ga. Additionally, one of the more evolved samples of the Giants Range Granite (fig. 3) has identical Nd systematics (table 1; fig. 5*A*). Thus, the Benson block is not clearly distinguishable from the Superior province on the basis of Nd isotopic composition alone. Our limited results are consistent with the petrologic observations by Southwick and others (1989) that the 3.5 Ga rocks found in other parts of the Minnesota River Valley may not be present in the Benson block.

Granitic rocks from cores BPL 2, 4, and 6 within the Benson block (fig. 2) have Nd isotopic compositions within the field of normal Superior province compositions (fig. 5*A*). If geochronology of the granites in these cores confirms Late Archean crystallization ages, they represent Late Archean crustal additions like much of the Superior province. Alternatively, given their geographic location between older Archean continental crust represented by the Ortonville Granite and Early Proterozoic continental crust across the Malmo discontinuity (fig. 2; fig. 5*A*, *D*), these granites could have crystallized in the Early Proterozoic, and their Nd systematics could be a result of mixing between these two end members.

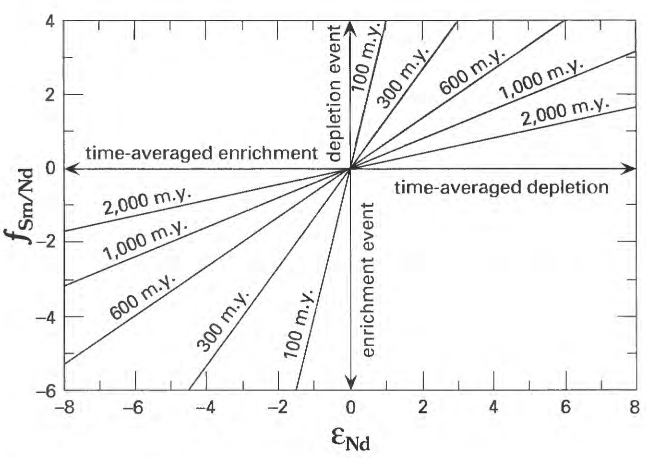

Figure 4. Generalized $f_{Sm/Nd}$ versus ε_{Nd} plot from Shirey (1984). Axes with arrows show the types of trajectories rocks will follow at their time of crystallization from a homogeneous source with ε_{Nd}=0 (vertical), and direction of change in ε_{Nd} with time in light rare earth element enriched and depleted reservoirs (horizontal). Radiating lines show the magnitude of evolution of ε_{Nd} with time.

Pre-Animikie Metasedimentary Rocks

Quartzofeldspathic units of the Mille Lacs Group, which overlies the McGrath Gneiss (fig. 3; fig. 5*C*, samples SRH 7, table 2), have Nd systematics indistinguishable from those of the McGrath Gneiss itself. Within the same series of outcrops, calc-silicate and amphibolitic rocks have high $f_{Sm/Nd}$ and also have Archean Nd model ages of 2.57 and 2.67 Ga. In contrast to samples from the eastern part of the McGrath–Little Falls terrane (terrane designation of Southwick and Morey, 1991; location 7, fig. 3; table 2), a phyllite within the Moose Lake–Glen Township terrane (location 5, fig. 3; table 2), also assigned to the Mille Lacs Group, has a T_{DM} of 2.07 Ga.

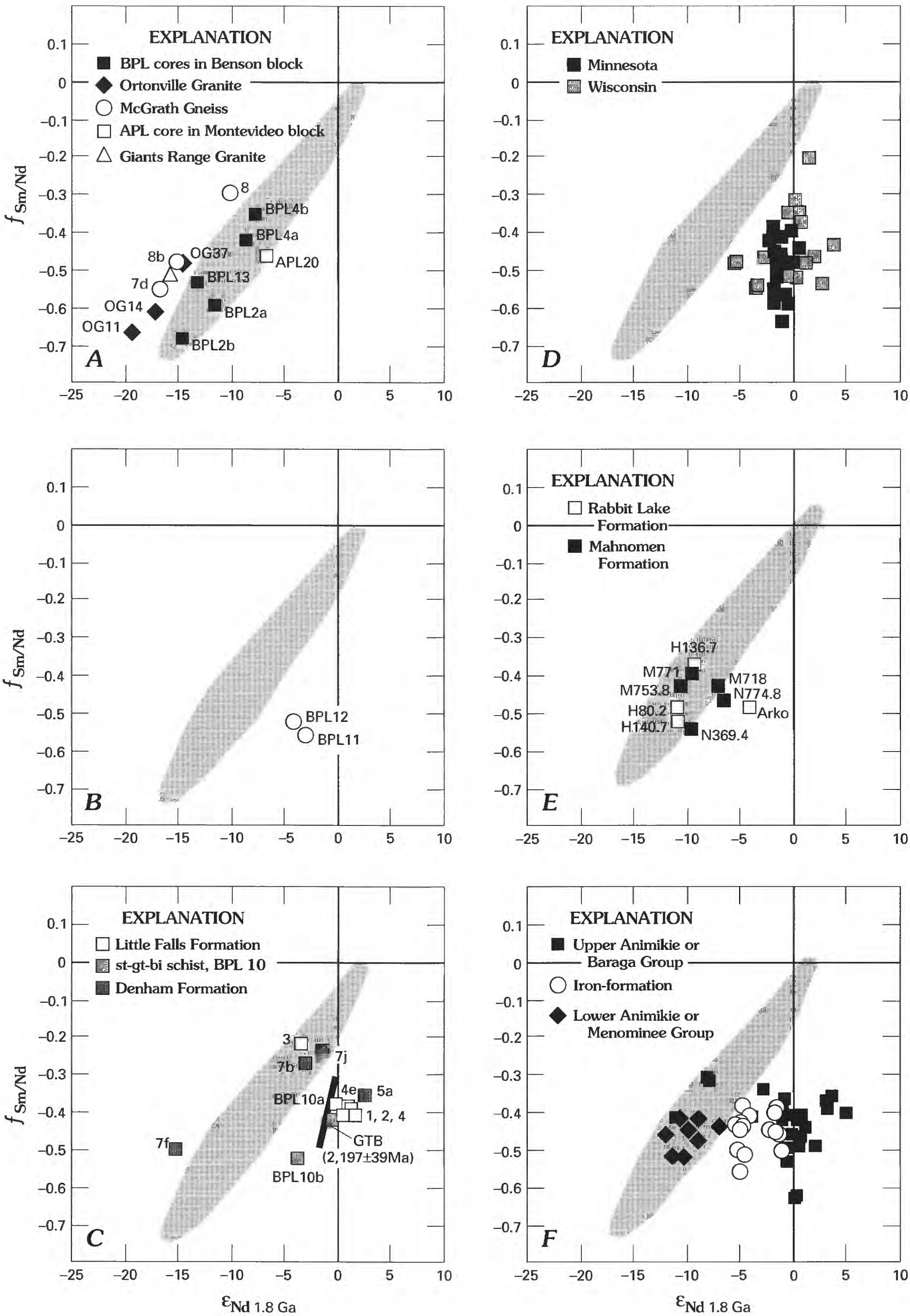
EXPLANATION
BPL cores in Benson block
Ortonville Granite
McGrath Gneiss
APL core in Montevideo block
Giants Range Granite
8
BPL4b
BPL4a
8b
OG37
APL20
7d
BPL13
OG14
BPL2a
OG11
BPL2b
A
EXPLANATION
Minnesota
Wisconsin
D
BPL12
BPL11
B
EXPLANATION
Rabbit Lake Formation
Mahnomen Formation
H136.7
M771
M753.8
M718
N774.8
H80.2
Arko
H140.7
N369.4
E
EXPLANATION
Little Falls Formation
st-gt-bi schist, BPL 10
Denham Formation
3
7j
7b
4e
5a
BPL 10a
1, 2, 4
GTB
(2,197±39Ma)
7f
BPL10b
C
EXPLANATION
Upper Animikie or Baraga Group
Iron-formation
Lower Animikie or Menominee Group
F
$f_{Sm/Nd}$
ε_{Nd} 1.8 Ga

Figure 5 (facing page). Plots of $f_{Sm/Nd}$ versus ε_{Nd} for samples discussed in this report. Shaded area, field of Superior province data from southern Ontario and northern Minnesota (Shirey and Hanson, 1986; Stern and Hanson, 1992). *A*, Plutonic samples from the Archean foreland and McGrath Gneiss (figs. 2, 3). Samples of the McGrath Gneiss have similar Nd isotopic systematics to the Ortonville Granite. (Numbers without prefixes, see SRH group, table 1.) *B*, Plutons east of Malmo discontinuity have Early Proterozoic model ages. *C*, Mille Lacs Group. Amphibolite and calc-silicate samples collected near the McGrath Gneiss have Late Archean model ages, and plot within Superior province field. Samples of the Little Falls Formation, including core samples from BPL 10, are dominated by Early Proterozoic sources, except one sample (3) that has systematics similar to the calc-silicates and amphibolite samples of the Denham area (SRH 7, table 2). (Numbers without prefixes, see SRH group, table 2.) Also shown for reference is a line (black) representing the data of Beck (1987) from the Glen Township Formation basalts (GTB (2,197±39 Ma)); st-gt-bi schist, staurolite-garnet-biotite schist. *D*, Published data from Wisconsin magmatic terranes in Wisconsin (Barovich and others, 1989) and Minnesota (Horan and others, 1987; Spencer, 1987). *E*, Data from the North Range Group of the Cuyuna district. These samples mostly have compositions consistent with a solely Superior province (or Benson block) derivation. *F*, Published data from the main bowl of the Animikie basin. Data from the Marquette Range Supergroup are from Barovich and others (1989); Pokegama Quartzite from Hemming and others (1994); Biwabik Iron-formation from Miller and O'Nions (1985) and Hemming and others (1995). Data from the Gunflint Iron-formation are from Stille and Clauer (1986), Jacobsen and Pimentel-Klose (1988), and Hemming and others (1992); Negaunee Iron-formation from Miller and O'Nions (1985); Rove, Tyler, and Virginia Formations from Hemming and others (1992, 1995).

Additionally, phyllitic samples from the Little Falls Formation at several locations in the western parts of the McGrath–Little Falls terrane (locations 1–4, fig. 3; table 2), with T_{DM} values of 2.14 to 2.18 Ga (one is 2.85, with very high $^{147}Sm/^{144}Nd$), were derived from a dominantly Early Proterozoic source. To the southwest of Little Falls (fig. 2), two samples of staurolite schist from core BPL 10, T_{DM}=2.26 and 2.36 Ga, also lie within the range of Early Proterozoic rocks of the Wisconsin magmatic terranes (fig. 5*C*, *D*), and may record mixing between Early Proterozoic and Archean sources.

Metasedimentary rocks from the Early Proterozoic North Range Group of the Cuyuna North range (figs. 3, 5*E*) record a substantial Archean component in their sources. The data permit that these sedimentary rocks are dominated by a ≈2.9 Ga mantle-derived source; however, one sample of the Rabbit Lake Formation (T_{DM}=2.45 Ga) probably records mixing of an Early Proterozoic source. Thus, mixing between Early Proterozoic and Middle Archean sources is also allowed by the data. Additionally, evidence of Early Proterozoic volcanic and hydrothermal fumarolic activity is recorded in the Trommald Formation (McSwiggen and others, 1992; Morey and others, 1992). Regardless of which scenario is correct, the rocks of the North Range Group record a substantially different source characteristic than do rocks of the upper Animikie Group (figs. 3, 5*F*). The Mahnomen and Rabbit Lake Formations, T_{DM}=2.6–3.0 Ga, have Nd isotope character similar to those of the Pokegama Quartzite (Hemming and others, 1994) and lower parts of the Marquette Range Supergroup (Barovich and others, 1989). These data are consistent with the new stratigraphic/structural hierarchy proposed by Southwick and others (1988) and Southwick and Morey (1991).

Plutons East of the Malmo Discontinuity

As mapped by Southwick and Morey (1991), the Malmo discontinuity (figs. 2, 3) traces a sharp southward bend in the Penokean orogen, and separates basement of Archean age in the Minnesota River Valley region from the McGrath Gneiss dome and the Early Proterozoic province of central Minnesota, which is most likely related to the Wisconsin magmatic terranes. Our results from Sm-Nd analysis of core samples are consistent with this mapping (fig. 5*B*). Granite samples from localities immediately west of the Malmo discontinuity (fig. 2, BPL 2, BPL 4) have T_{DM} values of 2.62–2.93 Ga. Two granites (BPL 11, BPL 12) and two samples of metasedimentary rocks (BPL 10a and b) from east of the discontinuity have T_{DM} from 2.28 to 2.38 Ga, similar to results from granitic and mafic igneous rocks in the St. Cloud area (Horan and others, 1987; Spencer, 1987). One sample (BPL 13), which was collected approximately on the boundary, has a T_{DM} of 2.93 Ga. Thus, there appears to be a rather abrupt change in the crust formation age that coincides closely with this geophysically mapped boundary. In the area of figure 3, the McGrath Gneiss, which is inferred to have been part of the Archean foreland, has T_{DM} of 3.11–3.29 Ga, identical to those from the Ortonville Granite. However, a large embayment of Early Proterozoic crust lies between the McGrath Gneiss dome and the Benson block, which includes the granitic and mafic igneous rocks of the St. Cloud area (Horan and others, 1987; Spencer, 1987), core samples from just east of the Malmo discontinuity (fig. 2), and possibly the Hillman Migmatite (unpublished U-Pb zircon age from S.S. Goldich).

The granitic rocks in the eastern part of the Benson block (BPL 2, BPL 4, fig. 2) could be Late Archean granites with mantle-like Nd isotopic compositions at their time of crystallization, such as seen for much of the Superior province. Alternatively, they could be Early Proterozoic granites with a large Archean crustal component in their sources. They are close to the Malmo discontinuity, and they have a younger range of Nd model ages than recorded in the Ortonville Granite or McGrath Gneiss (T_{DM}=2.74–2.92 versus 3.01–3.29 Ga). Full understanding of the nature of interaction between the Archean crust of the Minnesota River Valley terranes and the Penokean orogen must be preceded by dating of these granitic rocks.

SUMMARY: CRUSTAL BLOCKS OF THE PENOKEAN OROGEN

Neodymium model ages are shown on a schematic north-south representation of the Penokean orogen, modified from Morey and Southwick (1993) (fig. 6). The Little Falls Formation of the McGrath–Little Falls terrane of Southwick and Morey (1991) is grouped with the Penokean magmatic terrane rather than with the McGrath Gneiss. This grouping is supported by the Nd model ages in the Little Falls Formation (mostly Early Proterozoic; table 2) and by aeromagnetic patterns.

More samples should be analyzed to better understand the complicated framework of the Penokean orogen. Specific targets should be samples of (1) Hillman Migmatite (H, fig. 3), and (2) unnamed metasedimentary rocks of the Cuyuna South range terrane, Mille Lacs Group rocks of the Cuyuna North range terrane, and metasedimentary rocks of the Emily district. Knowing the isotopic compositions of some of the potentially correlative units within the Long Prairie basin and Nimrod outlier, interpreted to be isolated remnants of strata in the Animikie basin (Southwick and others, 1988) (fig. 3), would also be valuable.

We can make some general conclusions concerning the relationships between structural boundaries and crustal ages in central Minnesota. The Penokean orogen (fig. 6) from south to north consists of:

1. An Early Proterozoic magmatic terrane that was derived from a depleted mantle source with some Archean crustal contamination (Horan and others, 1987; Spencer, 1987). Metasedimentary rocks within this terrane have dominantly Early Proterozoic sources.

2. A block or blocks of Archean crust represented by the McGrath Gneiss and the Benson block. Metasedimentary rocks within this terrane have Archean model ages.

3. A foreland fold-and-thrust belt. Metasedimentary (SRH 5a, this study) and metavolcanic (Beck, 1987) rocks within the Moose Lake–Glen Township terrane of the fold-and-thrust belt have Early Proterozoic Nd model ages, whereas metasedimentary rocks in the North Range Group of the Cuyuna district have Archean model ages.

Within the main bowl of the Animikie basin, a progression in sources is recorded, from lower to higher stratigraphic levels and from north to south (Hemming and

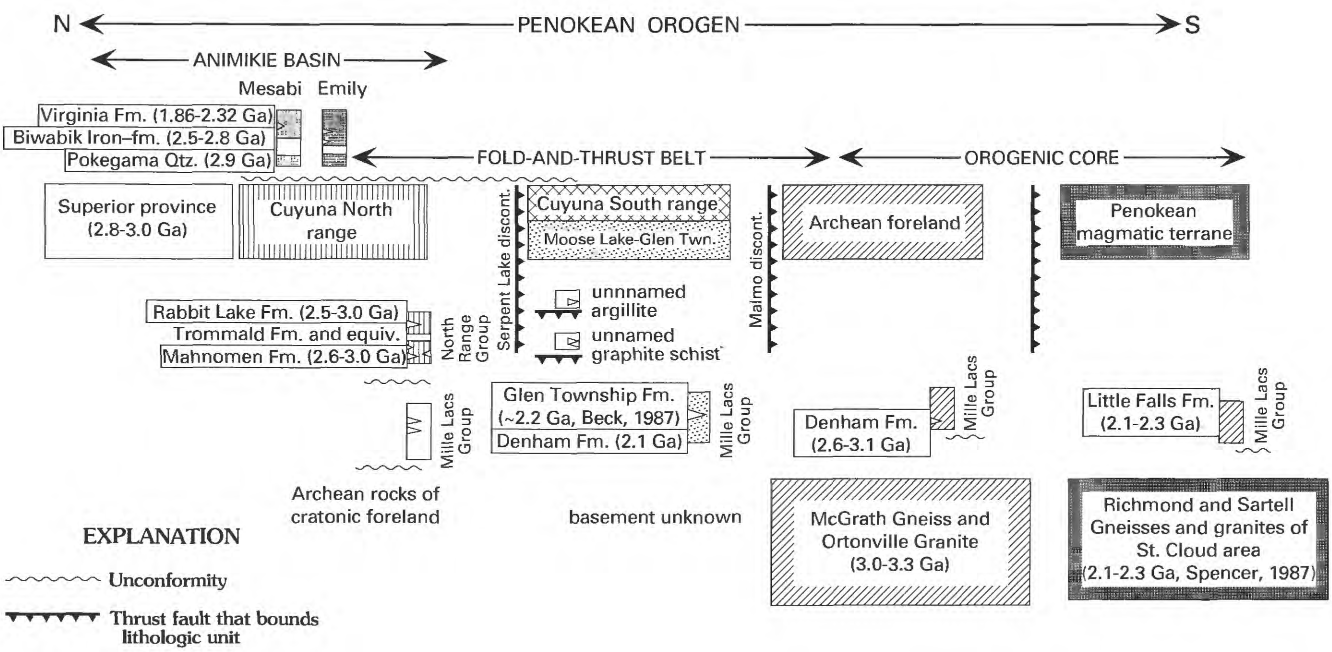

Figure 6. Depleted mantle model ages for Nd in structural-stratigraphic units. Modified from Morey and Southwick (1993).

others, 1995). Stratigraphically lower units within the Animikie basin, including the Pokegama Quartzite (Hemming and others, 1994, 1995) and the lower Marquette Range Supergroup (in Michigan) (Barovich and others, 1989) have Archean model ages. Iron-formations, located at intermediate stratigraphic positions, have a range of Nd model ages indicating mixing between Archean and Early Proterozoic Nd sources. Most of the younger units record Early Proterozoic model ages (Hemming and others, 1995) including Virginia, Thomson, Tyler, Rove, and Michigamme Formations. Exceptions can be found. (1) Some samples of the Rove Formation, which is located in the northern part of the presently preserved Animikie basin, have a T_{DM} of 2.55 Ga (Hemming and others, 1995); and (2) some northern samples of the Michigamme Formation in Michigan have T_{DM} from 2.70 to 3.09 Ga (Barovich and others, 1989).

The isotopic data presented here, gleaned from diverse blocks and assemblages, are consistent with current geology- and geophysics-based interpretations of central and southwestern Minnesota. The coincidence of the geophysical boundaries with rocks having substantial differences in Nd isotopic characteristics provides important support for both approaches, and supports the presence of important discontinuities between some of these crustal blocks. The Nd isotopic compositions and model ages add useful constraints on the crustal history of the various structurally and stratigraphically defined units. Many data are necessary in such a complex region, and more Nd isotopic mapping in conjunction with additional geologic and geophysical mapping could permit close comparisons of this region with specific aspects of the Early Proterozoic evolution of the midcontinent of North America.

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