Reinterpretation of Paleoproterozoic accretionary boundaries of the north-central United States based on a new aeromagnetic-geologic compilation

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ABSTRACT
The Paleoproterozoic crust in the north-central U.S. represents intact juvenile terranes accreted to the rifted Archean Superior craton. A new tectonic province map, based on the interpretation of a new aeromagnetic compilation, published geologic maps, and recent geochronologic data, shows progressive accretion of juvenile arc terranes from ca. 1900-1600 Ma. Contrary to earlier models, geon 18 Penokean-interval crust is primarily constrained to a ~2100 Ma tectonic embayment of the rifted Superior craton. The newly defined Spirit Lake tectonic zone, characterized by a sharp magnetic discontinuity that marks the southern limit of Archean and Penokean-interval rocks, is here interpreted to represent an eastern analog of the Cheyenne belt suture zone in southern Wyoming. South of this boundary, geon 17 Yavapai-interval rocks form the basement upon which 1750 Ma rhyolite and succeeding quartzite sequences were deposited. Much of the newly accreted Penokean and Yavapai terranes were subsequently deformed during the 1650-1630 Ma Mazatzal orogeny; the northern boundary of Mazatzal terrane is obscured by abundant 1470-1430 Ma "anorogenic" plutons that stitched the suture. These data reveal a progressive tectonic younging to the south as the Laurentian craton grew southward and stabilized during the Proterozoic. Late Mesoproterozoic rift magmatism produced pronounced geophysical anomalies, indicating strong, but localized crustal modification. In comparison to the western U.S., little tectonism has occurred here in the last one billion years, providing a uniquely preserved record of the Precambrian evolution of the continental U.S. lithosphere.

INTRODUCTION

The Upper Great Lakes region of the north-central United States has, for decades, been the linchpin for broader interpretation of the Precambrian assembly and evolution of Laurentia at the heart of the North American continent. Bordering the Archean Superior Province, the 1875-1835 Ma Penokean orogen (Van Schmus, 1976) has long been considered the predominant Paleoproterozoic collisional belt in the Great Lakes region, and has been extrapolated across much of the buried basement to the northeast and southwest (Fig. 1; Van Schmus et al., 1987; Sims et al., 1993). In comparison, younger 1780-1720 Ma Yavapai-interval crustal material is dominant south of the Archean Wyoming Province in the western U.S., residing across a documented geon 17 paleosuture known as the Cheyenne Belt (Karlstrom and Houston, 1984; Karlstrom and Humphreys, 1998; Crosswhite and Humphreys, 2003). Furthermore, in the better exposed western U.S., the 1800-1600 Ma Proterozoic accretionary history is complex, with multiple periods of island arc generation and accretion along the southern margin of Laurentia. We propose that a similarly complex accretionary history of juvenile crustal growth in the north-central U.S. has been largely hidden by poor-exposure and lack of significant topography across the region. This new interpretation is based on integration of new, revised and published data from geophysical, geochronological and bedrock geological mapping investigations. Our new Proterozoic tectonic province map reveals a southward progression of arc accretion during the late Paleoproterozoic, and provides important constraints on the growth and evolution of the southern Laurentian continent.

AEROMAGNETIC COMPILATION

Magnetic anomaly data provide a first-order image of lithologic variations and structural features in areas having little to no bedrock exposures. In North America where the southern edge of Canadian Shield disappears beneath mantling sedimentary rocks, these data allow us to
"see through" both the extensive non-magnetic cover of Pleistocene glacial deposits in the north, and, with almost equal effect, the magnetically transparent cover of flat lying Paleozoic and Mesozoic sedimentary rocks in the south. Importantly, magnetic anomaly patterns reveal variations in distribution and type of magnetic minerals in the Precambrian basement – characteristics reflecting both the composition and geometry of the otherwise largely inaccessible crust. Figure 2 is a high resolution, regional aeromagnetic map compiled from original acquisitions by the U.S. Geological Survey, the Geological Survey of Canada, and the Geological Surveys of Minnesota, Wisconsin, and Iowa. Our interpretation of this compilation (Fig. 3), aided by sparse outcrops and bedrock drill hole information (cf. Van Schmus et al., 2007), brings to light the Paleoproterozoic sutures and terranes inferred to be responsible for growth of the continental interior. In this paper, we use the terms Penokean, Yavapai, and Mazatzal to denote episodes of arc formation and rapid accretion at 1.9-1.8 Ga, 1.8-1.7 Ga, 1.7-1.6 Ga respectively.

**Rifted Archean framework.** The aeromagnetic image documents a collage of Precambrian terranes ranging in age from about 3.5 Ga to 1.1 Ga. The dominant geophysical signature is the 1100 Ma Midcontinent Rift (MCR) magnetic high extending from the shores of Lake Superior in the northeast to the southwest corner of the study area (Chandler et al., 1989). To the west of the MCR, the Archean craton is subdivided by the Great Lakes tectonic zone (GLtz), a late Neoarchean suture (Fig. 2; Sims et al., 1980). North of the GLtz are ca. 2750-2600 Ma east-northeast trending greenstone-granite terranes which extend into Canada, whereas to the south are 3400-3600 Ma gneisses of the Minnesota River Valley (MRV) subprovince (Goldich and Hedge, 1974; Bickford et al., 2006). The MRV subprovince is composed of four crustal blocks bounded by three zones of east-northeast-trending linear geophysical anomalies (Southwick and
Chandler, 1996). Totaling at least ca. 1400 km in length, the GLtz extends towards the east to just south of Lake Superior where Neoarchean granite-greenstone units are tectonically juxtaposed against Mesoarchean tonalities and granodiorites exposed in the cores of Paleoproterozoic gneiss domes (Sims and Day, 1993; Schneider et al., 1996)

Middle Paleoproterozoic rifting along the southern margin of the Archean craton was accompanied by the generation of a broad, radiating swarm of 2077-2067 Ma diabase dikes (Beck and Murthy, 1982; Schmitz et al., 2006). In northern Minnesota, a 300 km x 300 km dike swarm transects the Archean magnetic signatures at a high angle. The aeromagnetic data indicate that the dikes fan from NNW trends along their east margin to WNW trends along the southwest margin, converging toward the Penokean orogen in east-central Minnesota (Fig. 2; Halls et al., 2006). Although controversial and presently debated, Roscoe and Card (1993) argued that the Wyoming Province represents a portion of the Archean continental landmass that rifted away from the southern margin of the Superior craton during this middle Paleoproterozoic rifting episode. In the Upper Great Lakes region, Paleoproterozoic rifting, regardless of the specific details, created a distinct and irregular continental margin shape, consisting of the Becker embayment and the MRV promontory (Fig. 2; Chandler et al., 2007). This geometry represents the framework / architecture of the southern margin of the Superior Province upon which subsequent Proterozoic crustal growth was superimposed (Schulz and Cannon, 2007).

1.9-1.8 Ga Penokean terrane. Bordering the Becker embayment to the north and lapping onto the Archean craton is the ca. 2300-1770 Ma "craton margin domain" assemblage (Fig. 3; Schneider et al., 2002). The older part of the assemblage, consisting of mature quartzites, carbonates and lesser glaciogenic deposits, is now known to have been deposited between about 2300 and 2200 Ma (Vallini et al., 2006), probably in rift or sag basins on an evolving continental
margin (Larue and Sloss, 1980). However, the dominant sedimentary and lesser volcanic rocks
overlying the craton margin, including the region’s famous iron formations, represent foreland
basin deposits formed during northward migration of a fold and thrust belt associated with
Penokean orogenesis starting about 1880 Ma (Hoffman, 1987). Basin sedimentation continued
through Penokean accretion and collision, and locally during post-orogenic collapse and geon 17
Yavapai-interval accretion (Heaman and Easton, 2005).

Within the Becker embayment, and continuing to the east, is an assemblage of tholeiitic and
calc-alkalic volcanic and granitoid arc rocks making up the Wisconsin magmatic terranes which
were grafted to the Superior craton during the accretionary phase of Penokean orogenesis (Van
Schmus, 1976, 1980). A northern segment, the Pembine-Wausau terrane, consists of an oceanic
arc that was accreted to the rifted craton margin at 1880-1860 Ma along the south-dipping
Niagara fault zone, subsequently deforming the continental margin into a fold-thrust belt and
foreland basin architecture (Fig. 3). A southern segment, the Marshfield terrane, consists of
Archean crystalline rocks and Paleoproterozoic supracrustal rocks that are at least partly ensialic
and somewhat younger than the Pembine-Wausau arc (Sims et al., 1989). In west-central
Wisconsin, the Marshfield terrane has an irregular Z-shaped aeromagnetic signature that is
distinct from that of the juvenile arc terrane to the northeast. The Marshfield terrane likely
represents an exotic Archean microcontinent which accreted onto the Pembine-Wausau arc along
the 1860-1840 Ma Eau Pleine shear zone (Sims et al., 1989). The results of detailed geologic
mapping, and geophysical and geochronologic studies reveal that the magmatic terranes accreted
during the Penokean-interval in northern Wisconsin extend west beyond the Midcontinent Rift
into the Becker embayment in east-central Minnesota (Jirsa et al., 1995; Boerboom et al., 1995;
Holm et al., 2005; Chandler et al., 2007). In east-central Minnesota, Penokean structures, which
typically strike east-west, begin to trend southwest and south, paralleling the oroclinal curvature of the Becker embayment.

**1.8-1.7 Ga Yavapai terrane.** In the region depicted in the southern half of the aeromagnetic image, sparse bedrock drill-core specimens and isolated Precambrian outliers of 1750 Ma potassic rhyolite, epizonal granite and overlying supermature Baraboo Interval quartzites represent the only Precambrian bedrock available for examination. The general lack of information regarding the bedrock to these supracrustal units and poor geochronologic control has historically hampered understanding of this important region. It is this area of little subsurface data that benefits greatly from analysis of the aeromagnetic compilation presented here.

In the southwest part of Figure 2, a sharp aeromagnetic discontinuity is defined by a marked southeastward decrease of about 400 nanotesla in the intensity of the magnetic fabric signature. This anomaly is interpreted to represent the abrupt southern termination of the Minnesota River Valley rocks that extend to the north as originally recognized by Anderson and Black (1983) and named by them the Spirit Lake Trend (Van Schmus et al., 1989). Here renamed the Spirit Lake tectonic zone (SLtz), the discontinuity trends east-northeast and is intruded (on the south side) by a large circular granitic body of low magnetic signature (Fig. 2). East of the Midcontinent Rift, the geophysical signature of the SLtz changes, in part because of the different magnetic fabric of the Penokean orogenic rocks to the north. However, it is clearly expressed by a sharp truncation of the irregular (Z-shaped) geophysical pattern described above for the largely Archean gneisses and lesser Paleoproterozoic rocks of the Marshfield terrane. Because the SLtz truncates the main Penokean sutures, which closed the Becker Embayment, as well as the newly accreted Penokean terranes to the north (Marshfield and Pembine-Wausau), it must be a post-Penokean structure.
Contrary to previous interpretations (Van Schmus et al., 1989, 1993), we infer here that the SLtz marks the northern extent of juvenile geon 17 Yavapai-interval crust and the southern extent of Archean and Penokean crustal material. We therefore interpret the SLtz to be a fundamental terrane boundary, analogous to the Cheyenne Belt suture zone in southern Wyoming, which also juxtaposes juvenile geon 17 crust accreted against the Archean block to the north, and transects geon 18 (Trans-Hudson) structures in southern South Dakota. The SLtz is here projected east along an abrupt offset in the Moho (deeper to the south) beneath Lake Michigan previously identified in GLIMPCE seismic surveys, but then attributed to the Eau Pleine shear zone (Cannon et al., 1991).

South of the SLtz, the geophysical character of the crust is dominated by a low magnetic signature that is punctuated by local magnetic highs associated with plutons. In this paper, we consider this region to be the Yavapai terrane, broadly defined as juvenile crust formed and rapidly accreted between 1.8-1.7 Ga (Karlstrom et al., 2001). This terrane is marked by abundant 1470-1430 Ma granitic plutons, part of an extensive suite of "anorogenic" magmatism that transects much of the southern part of the North American continent (Anderson, 1983). In central Wisconsin, large granitic plutons are resolved geophysically as a generally smooth aeromagnetic pattern and low gravitational attraction, and locally manifested at the surface as the Wolf River batholith north of the SLtz. Other high-relief, high-intensity circular magnetic anomalies within the Yavapai terrane of central and western Iowa apparently delineate related granitic plutons (Van Schmus et al., 1989). Finn and Sims (2005) recognize identical magnetic and non-magnetic plutons of similar age in aeromagnetic surveys from the Rocky Mountain region. We note that these plutons are absent in the Archean crust north of the SLtz, a characteristic which holds true continent wide (Anderson, 1983).
1.7-1.6 Ga Mazatzal terrane. South of the SLtz and west of Lake Michigan, the structural fabric indicated by the aeromagnetic data is subparallel to the SLtz (Fig. 2). The aeromagnetic pattern there reveals an extensive area of folded Yavapai crystalline basement, 1750 Ma rhyolite, and 1730-1650 Ma Baraboo Interval quartzites beneath thin Paleozoic cover. These Paleoproterozoic rhyolites and quartzites were deposited between Yavapai and Mazatzal events in the north-central U.S. and deformed during geon 16 Mazatzal orogenesis (Dott, 1983; Holm et al., 1998b), the well known Baraboo synclinal structure (Fig. 3) having formed at this time. The Yavapai-Mazatzal terrane boundary must therefore be located southeast of these deformed rocks. Our dashed line on Figure 3 delineating an inferred northeast-trending Mazatzal suture is drawn south of all known Baraboo Interval quartzite localities. The study area is bordered in the southeast by a northeast-trending line of large irregularly shaped magnetic highs associated with the Green Island plutonic belt along the north edge of the geon 14 Eastern Granite-Rhyolite province (Van Schmus et al., 1993). The age of the country rocks into which these plutons intruded is unknown although Sm-Nd isotope data (Van Schmus et al. 1996) suggest the host terrane is late Paleoproterozoic (Mazatzal?). Given the deformation of the quartzites to the north (Holm et al., 1998b), the recent evidence for geon 16 amphibolite facies metamorphism north of the Green Island plutonic belt (Van Schmus et al., 2007), and projection of the Mazatzal suture along strike from the southwest U.S., we infer that the Mazatzal age crust exists in the southeast corner of the aeromagnetic compilation.

1100 Ma aborted rifting. The final major Precambrian event in the region was an aborted intracontinental rifting event at 1100 Ma that created the Midcontinent Rift (Hinze et al., 1997). The mafic magmatic rocks associated with the rift generate a profound magnetic and gravity anomaly that can be traced along a 2500 km long, arcuate path across the midcontinent (Fig. 3).
The rift transects terrane boundaries at a high angle and is filled with 10 to 25 km of flood basalts, comagmatic intrusions, and overlying clastic rocks accumulated in and near a series of grabens (Chandler et al., 1989). Although rifting may have nearly breached the continental crust, relatively little effect is evident beyond 100 km or so from the rift axis. Whether or not there are broader manifestations of these events in the deeper parts of the lithosphere remains to be determined. The geophysical data show that the southwestern arm of the rift, which cuts across eastern Minnesota, is dramatically offset to the southeast near the Iowa border. This deflection of the rift occurs in the proximity of the MRV promontory in the Becker embayment, implying that this ancestral Paleoproterozoic structure may have remained a strong crustal rampart well into the Mesoproterozoic.

**GEOCHRONOLOGIC SUMMARY**

A wealth of new geochronologic information from the Upper Great Lakes region supports the multi-accretionary history advanced here based on the aeromagnetic compilation. For instance, new basement geochronology from several localities south of the SLtz yield primary U-Pb zircon ages between 1800 and 1730 Ma (Van Schmus et al., 2007). To our knowledge, all presently available U-Pb ages from this region support our interpretation that the Yavapai terrane extends eastward from the central Rocky Mountains, through Nebraska and into Iowa and southern Wisconsin (Fig. 2), and that geon 18 Penokean-interval crust is largely absent from provinces south of the SLtz.

Metamorphic, intrusive, and cooling age data from the cratonic margin domain and the Pembine-Wausau terrane (Fig. 3) record a strong geon 17 age overprint probably related to accretion of Yavapai terranes to the south (Holm et al., 1998a, 2005, 2007; Schneider et al., 2004). Thus, the dominant tectonometamorphic signature of the highest grade Paleoproterozoic
rocks in the region is from the Yavapai-interval, not the geon 18 Penokean orogeny as historically envisioned. Yavapai accretion caused widespread plutonism and gneiss dome formation during tectonic extrusion of the buried continental margin rocks north of the Niagara fault zone (Schneider et al., 2004). Across the region, Yavapai accretion, magmatism, and exhumation were followed by a period of regional tectonic quiescence, crustal stabilization, and deposition of supermature 1730-1650 Ma Baraboo Interval quartzites (Dott, 1983; Holm et al., 1998b).

Across much of the Wisconsin Precambrian bedrock, moderate reheating caused by geon 16 Mazatzal accretion and foreland deformation was responsible for resetting of mica cooling ages. Interestingly, the northern limit of Mazatzal deformation and reheating is approximately coincident with the Niagara Fault zone in northern Wisconsin and upper Michigan (Holm et al., 1998b). In Minnesota, the Mazatzal deformational front must curve south of the Minnesota River Valley Promontory as those rocks are not isotopically reset (Goldich et al., 1961) and are overlain by flat-lying Sioux quartzite of the Baraboo Interval. This observation is consistent with our interpretation that the MRV block behaved as a rigid promontory that likely influenced subsequent Proterozoic tectonic architecture across this region.

**SUMMARY**

The north-central United States region straddles several geologic terranes and their primary terrane boundaries, including the transition from Archean tectosphere to juvenile Paleoproterozoic lithosphere. The new aeromagnetic compilation, in combination with regional geochronology, suggests a complex, yet distinctive pattern of crustal growth related to the Precambrian assembly of southern Laurentia. In the north, aeromagnetic data help delineate Paleoproterozoic sutures and deformational boundaries that reflect complexities related to
collision along an embayed continental margin, specifically the Becker embayment and Minnesota River Valley promontory. The Paleoproterozoic rift margin of the Upper Great Lakes probably evolved as a transform fault and upper-plate type margin in a manner analogous to the Late Precambrian-Cambrian rifted margin of the southeastern Appalachians (Schulz and Cannon, 2007; Thomas, 1993, 2006). Further, the data illustrate significant structural and magmatic modification of the Paleoproterozoic crust, likely related to the long-lived convergent nature of southern Laurentia (Karlstrom et al., 2001) that resulted in orogenic collapse structures and progressively younger deformational fronts to the south.

We argue here that the SLtz is a fundamental Yavapai-interval Paleoproterozoic boundary analogous to, although not necessarily physically linked with, the Cheyenne Belt suture zone in southern Wyoming. If correct, the SLtz is a fundamental feature of the tectonic evolution of the southern margin of Laurentia, the North American craton. Our new interpretation of the Paleoproterozoic continental growth and evolution of the northern interior of the North American craton suggests greater correspondence to that of the central and southern Rocky Mountains than previously recognized. In the Rocky Mountains, Paleoproterozoic terranes have been structurally and magmatically modified during Cenozoic and older tectonism. In comparison, relatively little tectonism has occurred in the cratonic interior during the last one billion years, providing a uniquely unaltered record of the Precambrian evolution of the North American continental lithosphere. The new two dimensional perspective presented here provides an important initial framework for upcoming further investigations of the deep structure of the continental interior.
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FIGURE CAPTIONS

Fig. 1: Map showing major Precambrian crustal provinces in the United States prior to formation of Mesoproterozoic igneous and tectonic provinces (modified after Van Schmus et al., 1993). Box denotes location of Fig. 2.

Fig. 2: Total field aeromagnetic anomaly compilation of the north-central United States. A detailed description of survey specifications for the individual data sets is available at the USGS Crustal Imaging and Characterizing Web Site at http://crustal.usgs.gov/geophysics/index.html. All data were gridded, continued to a common elevation of 305 meters above surface, and merged into a common grid.

Fig. 3: Proposed geologic terrane map of Precambrian basement rocks in the northern U.S. continental interior. WRB: Wolf River batholith. Underlying gray-toned base map is the newly compiled regional aeromagnetic anomaly map (Fig. 2). "Craton margin domain" represents sedimentary and volcanic rocks deposited during the interval 2.3 to 1.77 Ga; stippled pattern represents area affected by Penokean deformation; cross-hatched pattern represents area termed 'gneiss dome corridor' which was affected by Yavapai-interval deformation (Schneider et al., 2004). GIPB: Green Island plutonic belt; BS: Baraboo syncline.
CB: Cheyenne Belt
GFtz: Great Falls tectonic zone
GLtz: Great Lakes tectonic zone
NFz: Niagara Fault zone
SLtz: Spirit Lake tectonic zone