MESOPROTEROZOIC OROGENESIS IN THE U.S.A.

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Introduction

The older core of Laurentia consists of Archean cratons welded together from 1900 to 1800 Ma by orogenic belts such as the Trans-Hudson orogen, with the coeval Wopmay and Penokean accretionary orogens forming along the NW and SE margins, respectively (Hoffman, 1989). The assembly of this core was effectively completed by 1800 Ma; the southern parts of this core are found in the northern United States (Fig. 1: Wyoming and Superior provinces, Trans-Hudson and Penokean orogens). Laurentia continued to grow southward (present coordinates) from about 1800 Ma to 1630 Ma (Van Schmus *et al.*, 1993), forming an accretionary belt (Inner Accretionary Belt) which extends from California eastward through the midcontinent region; it may continue northeastward along the eastern margin of the older craton in Canada. From 1700 to 1600 Ma additional accretion may have occurred, but the dominant record is of continental margin tectonism (Outer Tectonic Belt) that may have been caused by a continental margin magmatic arc (Andean-type margin).

Prior to 1600 Ma Laurentia may have been part of a larger supercontinent (e.g., Rogers, 1996), but the >1600 Ma orogenic belts appear truncated along the SE margin of Laurentia, suggesting that part of this supercontinent may have rifted away before 1500 Ma (Van Schmus *et al.*, 1996). Alternatively, the orogenic belts in question may have been discontinuous or of variable width along the southeastern and eastern margin of Laurentia. In any case, by the close of the Paleoproterozoic the southern and eastern margins of Laurentia became inactive.

The first geon (100 m.y.) of the Mesoproterozoic (Geon 15: 1600 to 1500 Ma; Hoffmann, 1990) in Laurentia was quiet, with the possible exception of rifting to form a new SE-E margin that extended from W Texas to Labrador. Soon after 1500 Ma several important tectonic regimes developed in southern Laurentia (United States): a) accretion of juvenile terranes along the SE margin of Laurentia in the USA and northward along the eastern margin of Laurentia in Canada (Gower, 1996; Rivers, 1997; Mosher, 1998; Davidson, 2000), b) extensive sedimentation in the NW to form the Belt basin (Sears *et al.*, 1998; Link, 1993; Anderson and Davis, 1995), and c) intraplate A-type magmatism that involved most 1900 to 1600 Ma crust in southern Laurentia (SW USA and midcontinent region: Van Schmus *et al.*, 1993, 1996). All three regimes were probably linked as part of a major geodynamic system in and around Laurentia from 1500 Ma to 1000 Ma.

Mesoproterozoic Terrane Accretion.

Although there is reasonable evidence for an active continental margin within the Grenville Province in NE Canada in Geon 14 (Gower, 1996; Rivers, 1997), there is at present only circumstantial evidence for accretion occurring at that time in the United States. The St. Francois Mountains of SE Missouri (SFM, Fig. 1) consist of high-silica granites and rhyolites that crystallized about 1470 Ma (Van Schmus *et al.*, 1993). In contrast to coeval plutons to the west, which have Sm/Nd model ages (TDM) in excess of 1.6 Ga, the igneous rocks in the St. Francois Mountains have TDM ages of about 1500 Ma, suggesting that they were derived from melting of an underlying juvenile Mesoproterozoic terrane. Van Schmus *et al.* (1996) argued that the inferred terrane probably formed by accretion of a juvenile arc to the margin of pre-1600 Ma Laurentia.

In SE Oklahoma, igneous rocks and orthogneisses of the Arbuckle Mountains (ARB, Fig. 1) have U/Pb crystallization ages of 1.37 to 1.39 Ga, with TDM ages of about 1500 Ma (Rohs *et al.*, 1999). These results are interpreted as showing that the igneous rocks of the Arbuckle Mountains may also be the product of melting 1500 Ma juvenile crust, although they formed about 100 m.y. later than those in SE Missouri. In neither case is the inferred older basement exposed. Nonetheless, the data argue strongly for ca. 1500 Ma accretionary terrane(s) outboard of the pre-1600 Ma craton; this formed the crust from which the Mesoproterozoic igneous rocks of SE Missouri and SE Oklahoma were derived.

There is substantial evidence for terrane accretion and eastward continental growth within the Grenville Province during Geons 13, 12, and 11 (Rivers, 1997; Davidson, 2000). Some terranes extend southward into the Adirondack Mountains of New York (McLelland *et al.*, 1996), and Grenville gneisses extend southward in the subsurface, with occasional outcrops as far south as Georgia (Rankin *et al.*, 1993). In most cases there is insufficient evidence to detail accretionary histories in the southern Grenville Province in the U.S., but the mere presence of these rocks argues for such eastward growth of Laurentia during the Mesoproterozoic.

Mosher (1998) recently presented a detailed summary of structures and age relationships for Grenvillian type basement (Llano province) in the Llano Uplift (LU, Fig. 1) of Texas, in which she recognized several distinct terranes. The oldest, the Coal Creek Domain, formed 1326 to 1275 Ma as an island arc complex that was subsequently accreted to the Laurentian mainland. The Valley Spring Domain (VSD) and the Packsaddle Domain (PSD) may have formed from ca. 1280 to 1230 Ma as forearc basins along mainland Laurentia; Sm/Nd TDM ages ranging from 1480 to 970 Ma in VSD, PSD, and post-tectonic granites indicates that older (pre 1600 Ma) continental crust did not contribute substantially to these rocks. Instead, the VSD and PSD basins were probably floored by Mesoproterozoic continental crust (e.g., 1500 to 1300 Ma accreted terranes. Mosher (1998) argued that the CCD was probably accreted after formation of the VSD and PSD, with collision occurring between 1150 and 1120 Ma, during the Grenville collision. Post-tectonic plutons and dikes were emplaced about 1100 to 1070 Ma. Mosher (1998) suggested that the CCD may have first been accreted to an inbound, colliding continent that subsequently formed the conjugate part of the Grenville orogen.

Mesoproterozoic rocks in West Texas do not represent accreted terranes. The 1380 to 1330 Ma Carrizo Mountain Group consists of metarhyolite, quartzite, phyllite, and metabasalt that formed in continental rift basins (e.g., Mosher, 1998; Bickford *et al.*, 2000). These basins may represent distal portions of the Southern Granite-Rhyolite province and be underlain by pre-1600 Ma continental crust. They were affected by Grenville-age tectonism, and the westward extension of the Grenville orogenic belt and Grenvillian accreted terranes presumably lies to the south in Mexico.

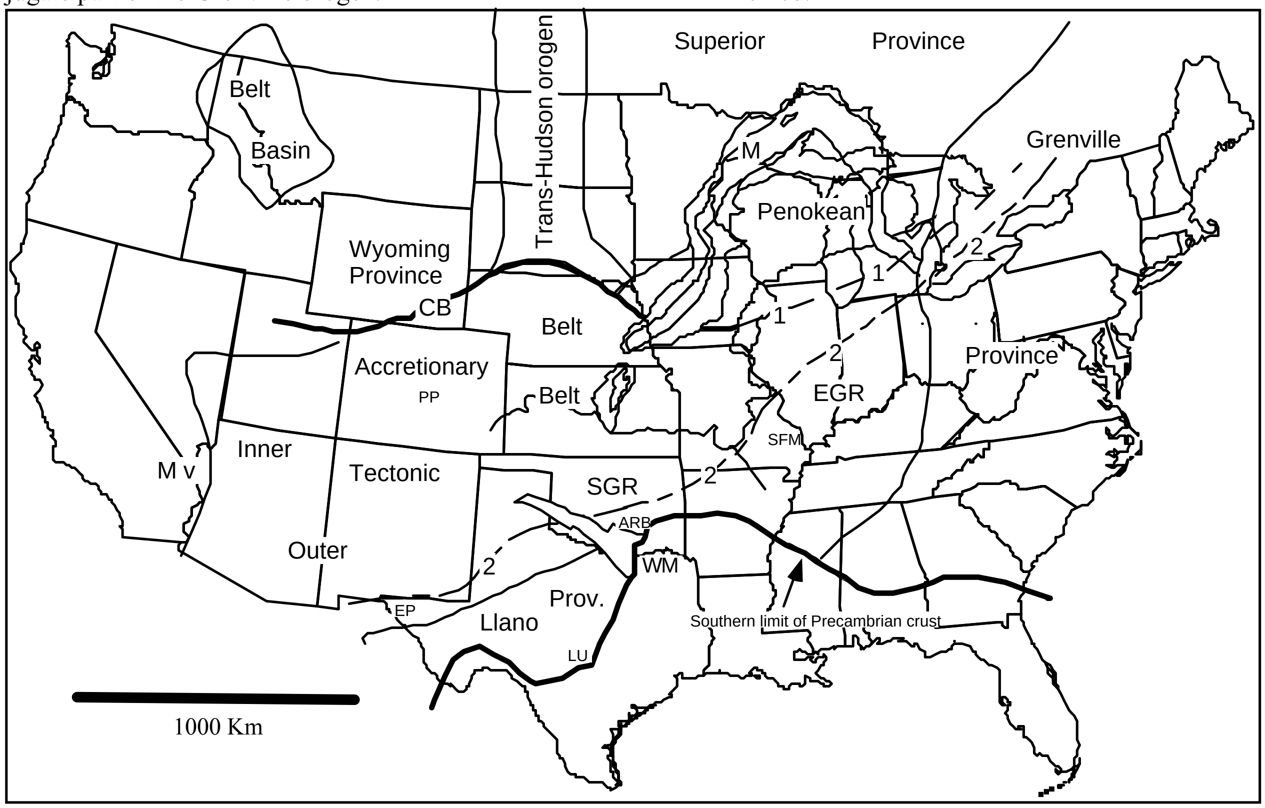

Figure 1. Generalized Precambrian basement geology of the United States (modified from Van Schmus *et al.*, 1993, 1996). Abbreviations: ARB = Arbuckle Mountains of Oklahoma; CB = Cheyenne Belt; EGR = 1.47 Ga Eastern Granite-Rhyolite province; EP = El Paso area, W Texas; LU = Llano Uplift of Texas; M = 1.1 Ga Midcontinent Rift System; Mv = Paleoproterozoic Mojave province (≥ 1.7 Ga); PP = Pikes Peak batholith of central Colorado; SFM = St. Francois Mountains of SE Missouri; SGR = 1.37 Ga Southern Granite-Rhyolite province; WM = Wichita Mountains rift zone (Cambrian); 1 = Inferred eastern limit of pre-1800 Ma crust; 2 = Inferred eastern limit of pre-1600 Ma crust . The Wyoming and Superior provinces are Archean (≥ 2.5 Ga); the Trans-Hudson and Penokean orogens are 1.9 to 1.8 Ga; the Inner Accretionary Belt is 1.7 to 1.8 Ga; the Outer Tectonic Belt is 1.7 to 1.6 Ga; the Belt Basin is 1.5 to 1.3 Ga.

Mesoproterozoic Sedimentation

The sedimentary record during the Mesoproterozoic falls into to four main categories: (a) the Belt-Purcell Supergoup of the NW U.S. and SW Canada (Fig. 1), (b) basins near or along the Mesoproterozoic continental margins, (c) basins within the interior of the continent, and (d) flanking basins associated with the 1.1 Ga Midcontinent Rift System.

The Belt-Purcell Supergroup, occurs in the NW U.S., with extensions northward into Canada (Link *et al.*, 1993). The Belt Supergroup contains as much as 16 km of siliciclastic and carbonate sedimentary rocks that were deposited on Archean to Paleoproterozoic basement of SW Laurentia. Recent geochronologic studies in the Belt Supergroup (Sears *et al.*, 1998; Anderson and Davis, 1995) have shown that it was deposited between 1500 Ma and 1300 Ma, with more than two-thirds of it deposited between

1470 Ma and 1440 Ma. The Belt basin is currently interpreted as a continental rift basin that initiated about 1470 Ma with significant pulses of rifting and subsidence occurring up to 1440 Ma; the basin may have been open to the ocean on the west. Doughty and Chamberlain (1996) also presented evidence for renewed, though less extensive, rifting and deposition about 1370 Ma.

Rocks of the second type occur in several places around the core of Laurentia. In the east and southeast, many such units are now high-grade schists and gneisses of the Grenville Province in Canada (Davidson, 2000) and the eastern U.S. (Rankin *et al.*, 1993) or lower grade deformed rocks of its foreland fold and thrust belts (e.g., West Texas: Mosher, 1998; Bickford *et al.*, 2000). The protoliths of the Grenville metasedimentary rocks range from pure carbonates to pure quartzites, with all ranges of siliciclastic and carbonate rocks included. Their tectonic settings range from passive margin to active margin environments, depending on the histories of individual terranes. There are several metasedimentary sequences that overlie Paleoproterozoic orogenic rocks in the SW U.S. In many cases their ages are poorly constrained, but some have been shown to been deposited during the late Mesoproterozoic (Link *et al.*, 1993) as passive margin or cratonic sequences. These sedimentary rocks indicate that the western margin of southern Laurentia was relatively stable during the Mesoproterozoic, except for rifting that may have formed local basins.

There are several candidates for rocks in the third category. Seismic reflection studies of the Midcontinent region east of the Mississippi River have revealed thick sequences of stratified rocks in what is collectively known as the Eastern Granite-Rhyolite province (EGR, Fig. 1; Van Schmus *et al.*, 1993; Rankin *et al.*, 1993). Granitic plutons about 1470 Ma old, and having juvenile TDM ages, have been encountered by drill holes in the central and western parts of the EGR (Van Schmus *et al.*, 1996), so if any of the layered reflectors in this region represent sedimentary units (presumably interlayered with EGR volcanic rocks), then they must be early Mesoproterozoic. Drill holes have also penetrated arkosic metasedimentary sequences in the easternmost part of the region, but there are no good constraints on their depositional ages. These units underlie basal Cambrian sandstones, but could range in age from Neoproterozoic to Mesoproterozoic; these sedimentary rocks are within-plate basins (Lidiak, 1966), attesting to general cratonic stability in the Midcontinent region during the Mesoproterozoic. Isolated arkosic basins to the west of the EGR, in SE Kansas and SW Missouri, were also thought to be Mesoproterozoic, but recent detrital zircons studies have shown that some of them must be Neoproterozoic.

The 1100 Ma Midcontinent Rift System (cf. Hinze *et al.*, 1997) includes several flanking sedimentary basins (cf., Anderson, 1997) that developed during early rifting and continued to develop during subsequent subsidence of the region after filling of the rift with mafic igneous rocks (see below).

Mesoproterozoic Rifting

There are several instances in which Mesoproterozoic rifting has been documented or inferred within the United States. The major rift event formed the Midcontinent Rift System (Fig. 1), beginning about 1108 Ma and lasting to about 1086 Ma (Hinze *et al.*, 1997). Recent petrologic, geochemical, isotopic, and geochronologic studies suggest that this system formed by rifting and magmatism associated with a major mantle plume that developed under Lake Superior. The largest arm of the rift system extended SW into the central U.S., a smaller arm extended SE into central Michigan, and a failed arm extended northward into the Lake Nipigon area of Canada. The rifting did not proceed to continental separation and drift because of compressional forces developed soon afterward in southern Laurentia as a result of the Grenville collision.

Other rifting events are more difficult to document, although in recent years there is growing evidence that the Belt-Purcell basin developed as a result of continental-margin rifting. Sears *et al.* (1998) argued for major rifting beginning about 1470 Ma and extending through 1440 Ma, with a second, smaller phase of rifting about 1370 Ma.

Mesoproterozoic A-type Magmatism

One of the major features of the Mesoproterozoic in the United States is the presence of abundant A-type plutons which intrude the Paleoproterozoic orogenic belts. There were two major episodes of A-type magmatism.

The first, and most wide-spread, episode began about 1500 Ma and lasted for about 80 m.y. Plutons associated with this episode extend from California in the SW United States, across the Midcontinent region (Van Schmus *et al.*, 1993), to Labrador in NE Canada (Gower, 1996; Rivers, 1997). The regional age of magmatism generally decreases westward, from the early part of Geon 14 in the east (1490 to 1450 Ma) to the latter part of this geon in the west (1450 to 1420 Ma). Therefore, the local durations of magmatism may have been significantly shorter (e.g., 10 or 20 m.y.), and the thermotectonic environment which caused crustal melting may have migrated with time.

The second large pulse of A-type magmatism occurred in the south-central United States during the early part of Geol 13, about 1400 to 1340 Ma, and is associated with formation of the the Southern Granite-Rhyolite province (cf. Van Schmus *et al.*, 1996). Rocks associated with this province may extend as far south as the Llano uplift of central Texas and the El Paso region of West Texas. Sm/Nd model ages (TDM) show that much of this province developed over continental crust equal to or younger than 1500 Ma.

In many cases, the petrology, chemistry, and Sm-Nd isotopic data of the 1500 Ma to 1340 Ma igneous rocks suggests within-plate genesis from Paleoproterozoic continental crust, and these plutons have commonly been called “anorogenic”. In recent years several investigators have noted deformation within and around these plutons, which suggests that they were, in fact, emplaced in a compressive or transpressive stress field that may have been an intra-plate response to continental margin orogenesis. Furthemore, recent studies of the Eastern Granite-Rhyolite province and the Southern Granite-Rhyolite province (Van Schmus *et al.*, 1996) showed that many of the A-type rocks were probably formed from melting of ca. 1500 Ma or younger basement (accreted terranes). In these cases, the magmatism may have been related to back-arc or within-arc extension of newly accreted material, and thus associated with continental margin orogenesis.

In spite of the variations noted above, probably the best explanation for genesis of the A-type plutonic belt is crustal melting associated with mafic underplating during a broad extensional regime. In this context it is important to note that the major rifting episodes associated with the Belt-Purcell Supergroup occurred at the same times (1470-1440 Ma, ca. 1370 Ma) as the major pulses of A-type magmatism. This is not inconsistent with continental margin orogenesis and compresive forces, since the overall extensional regime could have been due to some form of distal back-arc tectonism or stresses generated elsewhere around the continent.

A third, areally restricted, A-type event occurred in central Colorado with the formation of the large, isolated, ca. 1080 Ma Pikes Peak batholith (Smith *et al.*, 1999). This plutonic complex is best explained by crustal melting (potassic series) and fractional crystallization of mafic underplating (sodic series). The batholith is not part of any regional trend or association, but it is coeval with the Grenville collision and late stages of the Midcontinent Rift System and may be a hinterland manifestation of this tectonic regime.

Summary

The orogenic history of the Mesoproterozoic in the United States can be summarized as:

- Geon 15 (1599-1500 Ma): No events recorded. Possible break-up of late Paleoproterozoic supercontinent?
- Geon 14 (1499-1400 Ma): Accretion along S-SE margin; 1490-1420 Ma A-type plutonic belt; formation of Eastern Granite-Rhyolite province; rifting in NW and deposition of Belt-Purcell Supergroup.
- Geon 13 (1399-1300 Ma): Accretion along E-SE-S margin; formation of Southern Granite-Rhyolite province; continued sedimentation in NW.
- Geon 12 (1299-1200 Ma): Accretion along E-SE-S margin.
- Geon 11 (1199-1100 Ma): Continued accretion along E-SE-S margin (Grenville Province); initiation of Midcontinent Rift System; possible cratonic sedimentation.
- Geon 10 (1099-1000 Ma): Major mafic magmatism in Midcontinent Rift System; Terminal Grenville collision; Pikes Peak batholith emplaced.

References.

Anderson, H. E., and Davis, D.W., 1995. U-Pb geochronology of the Moyie sills, Purcell Supergroup, southeastern British Columbia: implications for the Mesoproterozoic geological history of the Purcell (Belt) basin. Canadian Journal of Earth Sciences, v. 32, p. 1180-1193.

Anderson, R.R., 1997. Keweenawan Supergroup clastic rocks in the Midcontinent Rift of Iowa. *In* Ojakangas, R.W., Dickas, A.B., and Green, J.C., editors, Middle Proterozoic to Cambrian Rifting, Central North America. Geological Society of America Special Paper 312, p. 211-230.

Bickford, M.E., Soegarard, K., Nielsen, K.C., and McLelland, J.M., 2000. Geology and geochronology of Grenville-age rocks in the Van Horn and Franklin Mountains area, West Texas: Implications for the tectonic evolution of Laurentia during the Grenville. Geological Society of America Bulletin, *in press*.

Davidson, A., 2000. Rodinia assembly, Grenville Province, Canada. This volume.

Doughty, P.T., and Chamberlain, K.R., 1996. The Salmon River arch revisited: new evidence for 1370 Ma rifting near the end of deposition in the Middle Proterozoic Belt Basin. Canadian Journal of Earth Sciences, v. 33, p. 1037-1052.

Gower, C.F., 1996. The evolution of the Grenville Province in eastern Labrador, Canada. *In* Brewer, T.S., ed., Precambrian Crustal Evolution in the North Atlantic Region, Geological Society (London) Special Publication No. 112, p. 197-218.

Hinze, W.J., Allen, D.J., Braile, L.W., and Mariano, J., 1997. The Midcontinent Rift System: A major Proterozoic continental rift. *In* Ojakangas, R.W., Dickas, A.B., and Green, J.C., editors, Middle Proterozoic to Cambrian Rifting, Central North America. Geological Society of America Special Paper 312, p. 211-230.

Hoffman, P.F., 1989. Precambrian geology and tectonic history of North America. *In* Bally, A.W., and Palmer, A.R., eds., 1989, The Geology of North America; An Overview: Geological Society of North America, The Geology of North America, v. A, p. 447-512.

Hoffmann, H.J., 1990. Precambrian time units and nomenclature - the geon concept. Geology, v. 18, p. 340-341.

Lidiak, E.G., 1996, Geochemistry of subsurface Proterozoic rocks in the eastern Midcontinent of the United States: Further evidence for a within-plate tectonic setting. *In* van der Pluijm, B.A., and Catacosinos, P., eds., Basement and basins of eastern North America. Geological Society of America Special Paper 308, p. 45-66.

Link, P. K., editor, and 12 others., 1993. Middle and Late Proterozoic stratified rocks of the western U.S.

Cordillera, Colorado Plateau, and Basin and Rang province. *In* Reed, J.C., Jr., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and Van Schmus, W.R., editors, Precambrian: Conterminous U.S. Boulder, Colorado, Geological Society of America, The Geology of North America, v. C-2, p. 463-595.

McLelland, J., Daly, J.S., and McLelland, J.M., 1996. The Grenville orogenic cycle (ca. 1350-1000 Ma): an Adirondack perspective. Tectonophysics, v. 265, p. 1-28.

Mosher, S., 1998. Tectonic evolution of the southern Laurentian Grenville orogenic belt. Geological Society of America Bulletin, v. 110, p. 1357-1375.

Rankin, D.W., editor, and 12 others, 1993. Proterozoic rocks east and southeast of the Grenville Front. *In* Reed, J.C., Jr., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and Van Schmus, W.R., editors, Precambrian: Conterminous U.S. Boulder, Colorado, Geological Society of America, The Geology of North America, v. C-2, p. 335-461.

Rivers, T., 1997. Lithotectonic elements of the Grenville Province: review and tectonic implications. Precambrian Research, v. 86, p. 117-154.

Rogers, J.J.W., 1996. A history of continents in the past three billion years. Journal of Geology, v. 104, p. 91-107.

Rohs, C.R., Van Schmus, W.R., Denison, R.E., Barnes, M.A., and Lidiak, E.G., 1999. Identifying Paleoproterozoic and Mesoproterozoic crustal domains within the Southern Granite and Rhyolite Province using Sm-Nd isotopes. Geological Society of America Abstracts with Programs, v. 31, no. 7, p. A-260.

Sears, J.W., Chamberlain, K.R., and Buckley, S.N., 1998. Structural and U-Pb geochronologicval evidence for 1.47 Ga rifting in the Belt Basin, western Montana. Canadian Journal of Earth Sciences, v. 35, p. 467-475.

Smith, D.R., Noblett, J., Wobus, R.A., Unruh, D., Douglass, J., Beane, R., Davis, C., Goldman, S., Kay, G., Gustavson, B., Saltoun, B., and Stewart, J., 1999. Petrology and geochemistry of late-stage intrusions of the A-type, mid-Proterozoic Pikes Peak batholith (Central Colorado, USA). Precambrian Research, v. 98. p. 271-305.

Van Schmus, W.R., Bickford, M.E., editors, and and 24 others, 1993. Transcontinental Proterozoic provinces. *In* Reed, J.C., Jr., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and Van Schmus, W.R., editors, Precambrian: Conterminous U.S. Boulder, Colorado, Geological Society of America, The Geology of North America, v. C-2, p. 171-334.

Van Schmus, W.R., Bickford, M.E., and Turek, A., 1996. Proterozoic geology of the east-central midcontinent basement. *In* van der Pluijm, B.A., and Catacosinos, P., eds., Basement and basins of eastern North America. Geological Society of America Special Paper 308, p. 7-32.