

Grenville foreland thrust belt hidden beneath the eastern U.S. midcontinent

Ernest C. Hauser Institute for the Study of the Continents, Cornell University, Ithaca, New York 14853

ABSTRACT

Grenville foreland thrust structures are observed beneath the eastern U.S. midcontinent on COCORP (Consortium for Continental Reflection Profiling) line OH-1 and a short seismic line in southwest Ohio. These structures represent the first evidence for a significant Grenville foreland thrust belt preserved in eastern North America. On the COCORP lines, the structures include a thrust ramp that truncates layered rocks of the footwall as well as a complex hanging-wall ramp anticline and an associated asymmetric syncline. The Grenville front tectonic zone appears to truncate these foreland structures, indicating a later, second phase, expressed as a deeply penetrating, out-of-sequence thrust zone associated with the main uplift of the Grenville province on the east. A short, shallow seismic line in southwestern Ohio reveals an east-dipping sequence of prominently layered rocks that may lie above a footwall ramp to a deeper Grenville thrust fault. A drill hole into the less reflective top of this dipping sequence encountered unmetamorphosed sedimentary rocks like those increasingly reported from other drill holes in southwestern Ohio and adjacent states. Although possibly part of a late Precambrian (Keweenaw?) rift, these clastic sedimentary rocks may instead preserve evidence of a heretofore unrecognized Grenville foreland basin in eastern North America. Alternatively, these Precambrian sedimentary rocks together with an underlying, but yet undrilled, strongly layered sequence may correlate with similarly layered rocks observed on COCORP and industrial seismic lines within the Middle Proterozoic granite-rhyolite province to the west in Indiana and Illinois and indicate that unmetamorphosed sedimentary material is an important constituent of the granite-rhyolite province. The presence of a Grenville foreland thrust belt beneath the eastern U.S. midcontinent, in contrast with its absence in Canada, may suggest a deeper level of erosion of the Grenville province and its foreland in Canada or reflect important lateral differences in the geology of the foreland.

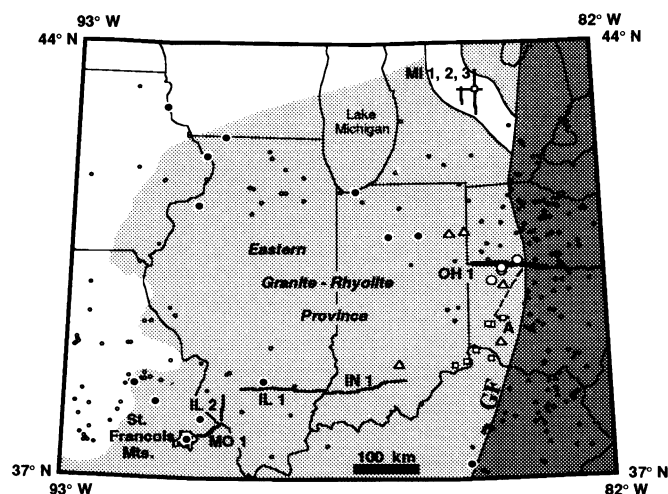
INTRODUCTION

The Grenville front, exposed in Canada as a prominent tectonic-metamorphic boundary, has been traced farther south beneath the Phanerozoic platform cover of the eastern United States by using scattered drill holes to basement and potential-field data (Bass, 1960; Summerson, 1962; Lidiak et al., 1966; Lidiak and Zietz, 1976; Denison et al., 1984; Lucius and Von Frese, 1988). In recent years, GLIMPCE (Great Lakes International Multidisciplinary Program on Crustal Evolution) data in northern Lake Huron (Green et al., 1988) and COCORP (Consortium for Continental Reflection Profiling) data across central Ohio (Figs. 1 and 2) (Pratt et al., 1989; Culotta et al., 1990) have imaged the Grenville front tectonic zone as a crustal-scale, east-dipping zone of strong reflections, both substantiating its location and demonstrating its remarkably similar structural expression over a distance of >500 km. As exposed in Canada, however, the foreland of the Grenville orogen has long puzzled geoscientists by the lack of a fold-and-thrust belt or foreland basin common to contractional orogens (Wynne-Edwards, 1972; Moore et al., 1986). Although some folding and faulting are observed northwest of the Grenville front in Canada, foreland deformation there is mainly characterized by a

dying out of rock cleavage away from the Grenville front over a distance of a few kilometres (i.e., Wynne-Edwards, 1972; Rivers and Chown, 1986). In contrast, as discussed below, structures beneath the Paleozoic platform cover on COCORP line OH-1 in western Ohio and other reflection data from southwest Ohio suggest the presence of thrust faults and associated folds within the Grenville foreland.

Figure 1. Map of basement provinces in eastern U.S. midcontinent. Light gray—eastern granite-rhyolite province (after Bickford et al., 1986); dark gray—Grenville province; GF—Grenville front; bold black lines—COCORP lines; A—short seismic line in southwestern Ohio (Fig. 4); white squares—drill holes into Precambrian sedimentary rocks (from Shrake et al., 1990, 1991); solid circles—drill holes in granite-rhyolite province sampled for zircon U-Pb age determinations (Bickford et al., 1986; Van Schmus et al., 1987);

open circles—drill holes into felsic and trachytic volcanic rocks near COCORP line (McCormick, 1961); open triangles—mafic rocks; small circles—other basement-penetrating drill holes; dashed line in southwestern Ohio—possible trend of Grenville foreland thrust ramp.

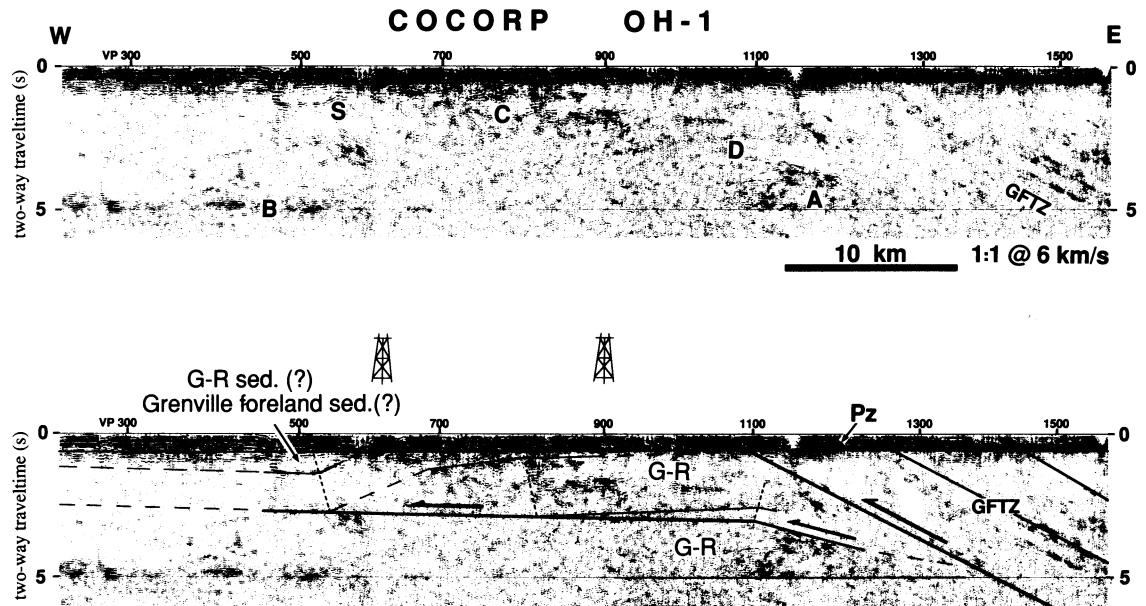


GRENVILLE FORELAND STRUCTURES ON COCORP LINE OH-1

Several structures observed on COCORP line OH-1 west of the Grenville front tectonic zone suggest a ramp-flat thrust geometry (Fig. 2). Immediately west of the tectonic zone, a series of subhorizontal reflections (3–5 s; A in Fig. 2; Fig. 3A) is truncated by a zone of ~14° east-dipping reflections suggesting a footwall thrust ramp. These truncated subhorizontal reflections appear to correlate with similar zones of reflections at comparable traveltimes to the west (B; Fig. 2) and may correlate regionally with similar reflections on COCORP line IN-1 and IL-1 farther west within or beneath the granite-rhyolite province (Pratt et al., 1989) or with a subhorizontal zone of reflections observed west of the Grenville front on GLIMPCE data (Green et al., 1988).

Near VP 500, a distinct zone of subhorizontal or gently east dipping reflections in the shallow basement turns up to the east, clearly indicating an asymmetric syncline (S in Fig. 2; Fig. 3B). This fold may identify the location of the ‘kink axis’ associated with the upper cutoff of the hanging-wall ramp, which may also be suggested by diffractions (below S; Fig. 2). Between this asymmetric syncline and the inferred thrust ramp, layered reflections in the shallow basement are discontinuous, irregular, and complicated by diffractions; however, in general, they appear gently arched (C–D in Fig. 2) and may indicate a complicated or disrupted ramp an-

Figure 2. Annotated and interpreted versions of part of COCORP line OH-1 across west-central Ohio (bold line, Fig. 1) suggesting foreland thrust structures within granite-rhyolite province rocks. GFTZ—Grenville front tectonic zone; Pz—Paleozoic platform cover; A, B, C, D, and S as described in text; G-R—granite-rhyolite province rocks. Well symbols show projected locations of basement-penetrating drill holes mentioned in text.



ticline. To the west of C, this layered sequence is not apparently imaged, possibly owing to steeper dips in the forelimb of the ramp anticline or to lateral variations within the layered rocks.

The Grenville front tectonic zone (Fig. 2) is imaged as a wide zone of planar reflections dipping $\sim 28^\circ$ east ($\sim 33^\circ$ when migrated) that truncates the foreland structures above and east of the ramp; therefore, this zone appears as an out-of-sequence thrust and younger than the foreland structures to the west. These relations suggest two phases in the evolution of the Grenville deformation here, foreland thrusting followed by a thicker-skinned phase of major uplift of the Grenville province.

ROCKS OF THE GRENVILLE FORELAND

West of the Grenville front in the eastern United States lies the eastern granite-rhyolite province, a region wherein drill holes to basement dominantly encounter epizonal granite or associated rhyolite from which analyzed zircons give U-Pb ages of 1480 ± 30 Ma (Fig. 1, solid circles) (Bickford et al., 1986; Van Schmus et al., 1987; Denison et al., 1984). The midcontinent (Keweenaw) rift system (~ 1.1 Ga) is traced through Lake Superior and into central Michigan, where it is observed on COCORP profiles (Fig. 1) (Zhu and Brown, 1986) and terminates at the Grenville front.

Rocks recovered from drill holes west of the Grenville front near the COCORP line (Fig. 1, open circles) are described as rhyolite and aphanitic volcanic rocks with abundant microcline (McCormick, 1961) and suggest that the foreland structures imaged on the COCORP line are largely developed in rocks of the granite-rhyolite province. For

example, core samples of rhyolite with flow banding are described from the Johns well in Logan County, Ohio (~ 5 km north of VP 900, Fig. 2), and trachyte porphyry with orthoclase phenocrysts are described from the Nelson well in Shelby County, Ohio (~ 22 km south of VP 575, Fig. 2) (McCormick, 1961). A recent reanalysis of basement samples in Ohio, however, indicates that K-feldspar authigenesis of both primary K-feldspar and albitic plagioclase is locally significant in the uppermost basement and also suggests that the samples from the Nelson well may instead be altered basalt (Lidiak and Ceci, 1991). Rb-Sr analysis of the rocks from the Johns and Nelson wells, however, gives apparent ages of 1240 ± 120 and 1280 ± 70 Ma, respectively (Lidiak et al., 1966), recalculated to 1284 and 1325 Ma (Lucius and Von Frese, 1988), which are old for Keweenaw (~ 1.1 Ga) but comparable to the anomalously young Rb-Sr ages typically found in the ~ 1.4 – 1.5 Ga granite-rhyolite province

elsewhere in Indiana, Illinois, and Missouri (Denison et al., 1984; Lidiak et al., 1966; Hoppe et al., 1983). From this it seems likely that the Grenville foreland thrust structures described above on COCORP line OH-1 are mainly developed in rocks of the granite-rhyolite province.

GRENVILLE FORELAND STRUCTURES AND THE PRECAMBRIAN SEDIMENTARY ROCKS BENEATH SOUTHWEST OHIO

Grenville foreland deformation may also be revealed by a short east-west seismic reflection line in southwest Ohio (A in Fig. 1). These data reveal a sequence of prominently layered Precambrian rocks dipping $\sim 10^\circ$ east (Fig. 4) that is locally deformed by an east-dipping reverse fault of minor displacement that does not affect the Paleozoic cover (Shrake et al., 1991). However, in light of the larger scale Grenville foreland structures observed on the COCORP data to the north and

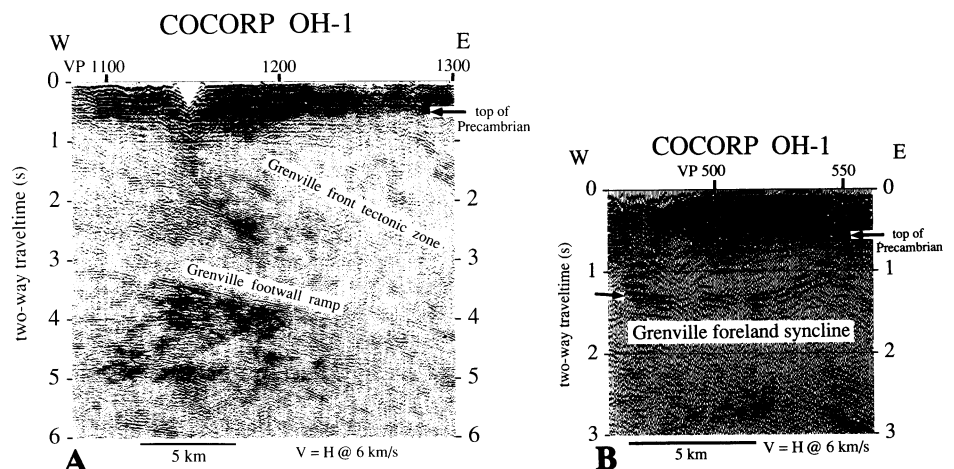


Figure 3. Enlargements of COCORP OH-1 data of Figure 2. A: Grenville footwall ramp and Grenville front tectonic zone. B: Asymmetric syncline in Grenville foreland.

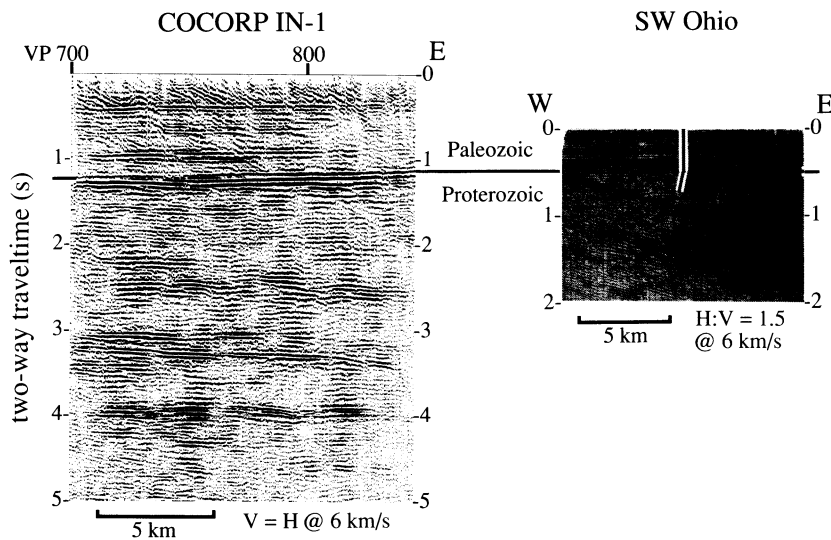


Figure 4. Comparison of short seismic line in southwestern Ohio (see location in Fig. 1) revealing dipping Precambrian layered rocks (from Shrake et al., 1990, 1991) with COCORP line IN-1 in south-central Indiana showing similar prominent layered sequence. Data are at same vertical scale, with base of Paleozoic cover aligned. Drill-hole location and depth shown on southwestern Ohio data; unmetamorphosed Precambrian clastic sedimentary rocks encountered below Paleozoic cover. V—vertical; H—horizontal.

the proximity of this short seismic line to the Grenville front ~25 km to the east, the east dip of this *entire* layered Precambrian sequence may result from its position above a footwall ramp to a deeper, more significant Grenville thrust fault.

A drill hole penetrated the upper, less reflective part of the dipping Precambrian sequence on this short seismic line (Fig. 4) and recovered unmetamorphosed clastic sedimentary rocks of the Middle Run Formation (Shrake et al., 1990, 1991), but it did not sample the deeper strong reflectors. The pattern of relatively nonreflective sedimentary rocks above strongly reflective volcanic flows is common in reflection studies of the Keweenaw rift (i.e., Serpa et al., 1984);

however, mafic rocks of the midcontinent rift system and those encountered in many drill holes (i.e., triangles in northeastern Indiana, Fig. 1) (Kottowski and Patton, 1953) are commonly associated with distinctive gravity and magnetic highs (Henderson and Zietz, 1958; Hinze et al., 1975). The prominently layered rocks imaged on this short seismic line, however, lie within a region of distinctly *low* potential field anomalies (i.e., Lucius and Von Frese, 1988) suggesting that mafic rocks are not a major constituent.

These strong reflectors greatly resemble, in both reflection prominence and lateral continuity, the layered sequence imaged on COCORP lines across southern Indiana and Illinois within the granite-rhyolite province

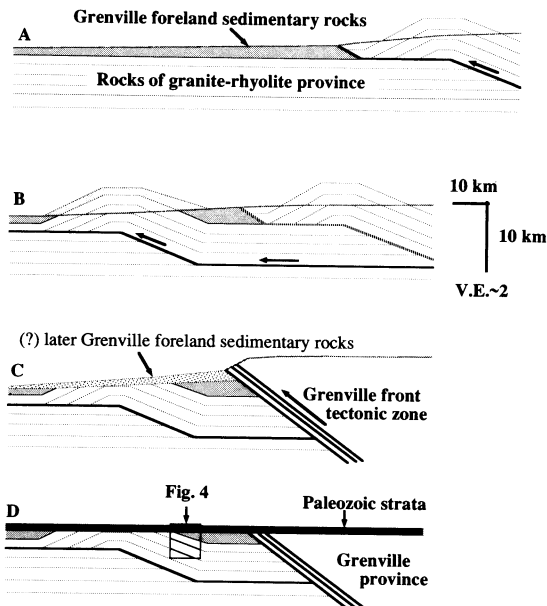


Figure 5. Grenville foreland thrust belt model; Precambrian sedimentary rocks (gray) deposited in Grenville foreland basin. Sequence of events outlined in text. Interpreted position of southwestern Ohio seismic data (Fig. 4) shown in part D. V.E.—vertical exaggeration.

(Figs. 1 and 4). Although the nature of the layered rocks of the granite-rhyolite province is not well known, they may comprise *silicic* volcanic or sedimentary rocks, perhaps intruded locally by mafic sills (Pratt et al., 1989, 1992).

The Middle Run Formation throughout southwest Ohio, southeast Indiana, and northern Kentucky and the underlying layered rocks may indeed be part of a poorly understood Precambrian (Keweenaw) rift. However, in light of the Grenville thrust structures on COCORP line OH-1 to the north and the similarity of the strongly layered rocks imaged beneath southwestern Ohio to those on COCORP data in Indiana and Illinois (Fig. 4), I would pose two other alternative hypotheses (Figs. 5 and 6). (1) Some of these Precambrian sedimentary rocks may be part of a Grenville foreland basin deposited upon older layered rocks of the granite-rhyolite province (Fig. 5A), or (2) the Middle Run Formation itself may be older and indicate that unmetamorphosed sedimentary strata are an important constituent of the strongly layered sequence within the granite-rhyolite province (Fig. 6A). In any case, these sedimentary and underlying layered rocks were likely deformed within a Grenville foreland thrust belt (Figs. 5B and 6B), were cut by the Grenville front tectonic zone as an out-of-sequence thrust zone that bounded the major uplift of the Grenville province (Figs. 5C and 6C), and were subsequently eroded and covered by Phanerozoic strata (Figs. 5D and 6D). The postulated fault-bend folds demarking the underlying

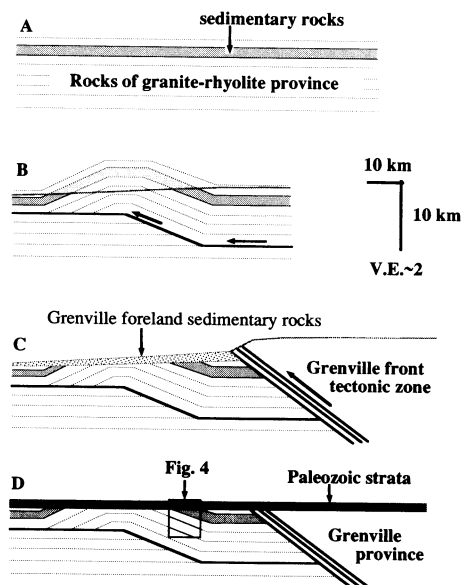


Figure 6. Grenville foreland thrust belt model; Precambrian sedimentary rocks as part of granite-rhyolite province layered sequence. Sequence of events outlined in text. Interpreted position of southwestern Ohio seismic data (Fig. 4) shown in D. V.E.—vertical exaggeration.

ramp would apparently lie farther east and west of the short seismic line (Figs. 5D, 6D).

The models in Figures 5 and 6 are consistent with both the data in southwestern Ohio and the foreland structures observed on COCORP line OH-1 to the north (Fig. 2). On the COCORP line, however, the Grenville front tectonic zone cuts out the foreland structures close to the thrust ramp (Fig. 2), whereas the inferred ramp in southwest Ohio would lie farther west. A correlation of these ramps along strike (Fig. 1, dashed line) might suggest a more southwestward trend for the foreland structures in relation to the Grenville front, an inference consistent with the preservation of the Precambrian sedimentary strata mainly southeast of the ramp in southwest Ohio and adjacent Indiana and Kentucky (Fig. 1). Whether such obliquity also indicates a sinistral component during Grenville deformation is even more speculative, but sinistral oblique convergence is consistent with (1) a change from the northeast trend and northwest convergence of the exposed Grenville front in Canada to the northern trend of the Grenville front in Ohio and (2) the opening of the midcontinent (Keweenaw) rift system in relation to southward tectonic escape during Grenville convergence.

This evidence for a significant Grenville foreland thrust belt beneath the eastern United States contrasts with that observed in surface exposures in Canada where the Grenville foreland structural expression across Archean and Early Proterozoic provinces is mainly one of a decrease in the development of rock cleavage over a distance of a few kilometres (i.e., Wynne-Edwards, 1972; Moore et al., 1986; Rivers and Chown, 1986). This difference may reflect a deeper level of post-Grenville erosion in Canada, a suggestion consistent with (1) the generally higher metamorphic grade in the Grenville province in Canada compared to that for Grenville rocks recovered from drill holes in Ohio (i.e., Bass, 1960; Summerson, 1962; Wynne-Edwards, 1972) and (2) the mere presence of the thick supracrustal sequence within the Middle Proterozoic granite-rhyolite province of the U.S. midcontinent (Bickford et al., 1986; Van Schmus et al., 1987; Pratt et al., 1989, 1992). A Grenville foreland thrust belt may also be better developed to the south *because* of the thick sequence of Precambrian supracrustal rocks there.

CONCLUSIONS

The evidence discussed here, suggesting significant Grenville foreland deformation concealed beneath the platform cover of the U.S. midcontinent, challenges the way geoscientists traditionally view the Grenville orogen and the nature of its foreland, though

the picture is far from complete. Perhaps it should not be surprising that the expression of the Grenville orogen might change where it encountered geologic provinces of different crustal and lithospheric structure and evolution. Moreover, the models presented here pose *testable* alternative hypotheses regarding the Precambrian crustal structure and tectonic evolution of the eastern U.S. midcontinent.

ACKNOWLEDGMENTS

Supported by U.S. Department of Energy grant DE-FG21-91MC28136, American Chemical Society Petroleum Research Fund grant 22309-AC2, and National Science Foundation grant EAR-8916129. I appreciate the comments of J. Oliver, M. Barazangi, L. Brown, and J. Drahovzal on an early draft and the considered remarks of W. Hinze and an anonymous reviewer. Institute for the Study of the Continents Contribution 178.

REFERENCES CITED

- Bass, M.N., 1960, Grenville boundary in Ohio: *Journal of Geology*, v. 68, p. 673-677.
- Bickford, M.E., Van Schmus, W.R., and Zietz, I., 1986, Proterozoic history of the midcontinent region of North America: *Geology*, v. 14, p. 492-496.
- Culotta, R.C., Pratt, T., and Oliver, J., 1990, A tale of two sutures: COCORP's deep seismic surveys of the Grenville province in the eastern U.S. midcontinent: *Geology*, v. 18, p. 646-649.
- Denison, R.E., Lidiak, E.G., Bickford, M.E., and Kisvarsanyi, E.B., 1984, Geology and geochronology of Precambrian rocks in the central interior region of the United States: U.S. Geological Survey Professional Paper 1241-C, 20 p.
- Green, A.G., and nine others, 1988, Crustal structure of the Grenville front and adjacent terranes: *Geology*, v. 16, p. 788-792.
- Henderson, J.F., Jr., and Zietz, I., 1958, Interpretation of an aeromagnetic survey of Indiana: U.S. Geological Survey Professional Paper 316-B, 37 p.
- Hinze, W.J., Kellogg, R.L., and O'Hara, N.W., 1975, Geophysical studies of basement geology of the southern peninsula of Michigan: *American Association of Petroleum Geologists Bulletin*, v. 59, p. 1562-1564.
- Hoppe, W.J., Montgomery, C.W., and Van Schmus, W.R., 1983, Age and significance of Precambrian basement samples from northern Illinois and adjacent states: *Journal of Geophysical Research*, v. 88, p. 7276-7286.
- Kottowski, F.E., and Patton, J.B., 1953, Precambrian rocks encountered in test holes in Indiana: *Indiana Academy of Science Proceedings*, v. 62, p. 234-243.
- Lidiak, E.G., and Ceci, V.M., 1991, Authigenic K-feldspar in the Precambrian basement of Ohio and its effect on tectonic discrimination of the granitic rocks: *Canadian Journal of Earth Sciences*, v. 28, p. 1624-1634.
- Lidiak, E.G., and Zietz, I., 1976, Interpretation of aeromagnetic anomalies between latitudes 37°N and 38°N in the eastern and central United States: *Geological Society of America Special Paper* 167, 37 p.
- Lidiak, E.G., Marvin, R.F., Thomas, H.H., and Bass, M.N., 1966, Geochronology of the midcontinent region, United States, Part 4. East-

- ern area: *Journal of Geophysical Research*, v. 71, p. 5427-5438.
- Lucius, F.E., and Von Frese, R.R.B., 1988, Aeromagnetic and gravity anomaly constraints on the crustal geology of Ohio: *Geological Society of America Bulletin*, v. 100, p. 104-116.
- McCormick, G.R., 1961, Petrology of Precambrian rocks of Ohio: Ohio Department of Natural Resources Report of Investigations No. 41, p. 60.
- Moore, J.M., Davidson, A., and Baer, A.J., eds., 1986, The Grenville Province: Geological Association of Canada Special Paper 31, 358 p.
- Pratt, T., Culotta, R., Hauser, E., Nelson, D., Brown, L., Kaufman, S., Oliver, J., and Hinze, W., 1989, Major Proterozoic basement features of the eastern midcontinent of North America revealed by recent COCORP profiling: *Geology*, v. 17, p. 505-509.
- Pratt, T.L., Hauser, E.C., and Nelson, K.D., 1992, Widespread buried Precambrian layered sequences in the U.S. mid-continent: Evidence for large Proterozoic depositional basins: *American Association of Petroleum Geologists Bulletin*, v. 76, p. 1384-1401.
- Rivers, T., and Chown, E.H., 1986, The Grenville orogen in eastern Quebec and western Labrador—Definition, identification and tectonometamorphic relationships of autochthonous, parautochthonous and allochthonous terranes, in Moore, J.M., et al., eds., *The Grenville Province: Geological Association of Canada Special Paper* 31, p. 31-50.
- Serpa, L., Setzer, T., Farmer, H., Brown, L., Oliver, J., Kaufman, S., Sharp, J., and Steeples, D.W., 1984, Structure of the southern Keweenaw rift from COCORP surveys across the Midcontinent Geophysical Anomaly in northeastern Kansas: *Tectonics*, v. 3, p. 367-384.
- Shrake, D.L., Wolfe, P.J., Richard, B.H., Swinford, E.M., Wickstrom, L.H., Potter, P.E., and Sitler, G.W., 1990, Lithologic and geophysical description of a continuously cored hole in Warren County, Ohio, including description of the Middle Run Formation (Precambrian?) and a seismic profile across core site: *Ohio Geological Survey Information Circular* 56, 11 p.
- Shrake, D.L., Carlton, R.W., Wickstrom, L.H., Potter, P.E., Richard, B.H., Wolfe, P.J., and Sitler, G.W., 1991, Pre-Mount Simon basin under the Cincinnati Arch: *Geology*, v. 19, p. 139-142.
- Summerson, C.H., 1962, Precambrian in Ohio and adjoining areas: *Ohio Geological Survey Report of Investigations* 44, p. 1-16.
- Van Schmus, W.R., Bickford, M.E., and Zietz, I., 1987, Early and Middle Proterozoic provinces in the central United States, in Kroner, A., ed., *Proterozoic lithospheric evolution: American Geophysical Union Geodynamics Series*, v. 17, p. 43-68.
- Wynne-Edwards, H.R., 1972, The Grenville Province, in Price, R.A., and Douglas, R.J.W., eds., *Variations in tectonic styles in Canada: Geological Association of Canada Special Paper* 11, p. 263-334.
- Zhu, T., and Brown, L.D., 1986, COCORP Michigan surveys: Reprocessing and results: *Journal of Geophysical Research*, v. 91, p. 11,477-11,499.

Manuscript received March 24, 1992

Revised manuscript received September 18, 1992

Manuscript accepted September 29, 1992