Seismic images of a Grenvillian terrane boundary

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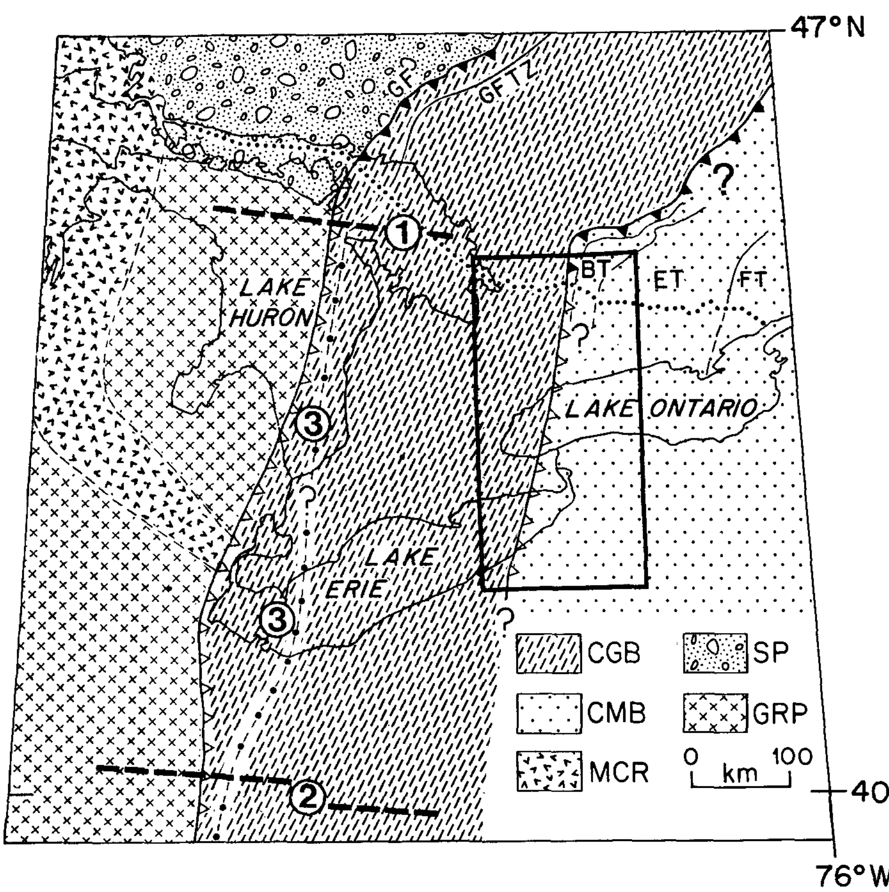
ABSTRACT

A series of gently dipping reflection zones extending to mid-crustal depths is recorded by seismic data from Lakes Ontario and Erie. These prominent reflection zones define a broad complex of southeast-dipping ductile thrust faults in the interior of the Grenville orogen. One major reflection zone provides the first image of a proposed Grenvillian suture—the listric boundary zone between allochthonous terranes of the Central Gneiss and Central Metasedimentary belts. Curvilinear bands of reflections that may represent "ramp folds" and "ramp anticlines" that originally formed in a deep crustal-scale duplex abut several faults. Vertical stacking of some curvilinear features suggests coeval or later out-of-sequence faulting of imbricated and folded thrust sheets. Grenvillian structure reflections are overlain by a thin, wedge-shaped package of shallow-dipping reflections that probably originates from sediments deposited in a local half graben developed during a period of post-Grenville extension. This is the first seismic evidence for such extension in this region, which could have occurred during terminal collapse of the Grenville orogen, or could have marked the beginning of pre-Appalachian continental rifting.



INTRODUCTION

The Middle Proterozoic Grenville orogen extends the length of eastern North America from Labrador to Mexico. During the past decade, deep seismic reflection data were collected across the Grenville front and adjacent parts of the Grenville orogen in Lake Huron (Green et al., 1988), Lake Erie (Forsyth et al., 1991), and Ohio (Pratt et al., 1989; Culotta et al., 1990). Compared to the relatively well studied western margin of the Grenville orogen, little is known about the deep geometry of terranes within its interior (Rivers et al., 1989). We present seismic reflection and aeromagnetic data from the western margin of the Central Metasedimentary belt, an important terrane boundary within the Grenville orogen.

REGIONAL GEOLOGIC SETTING

About 300 km west of the study area, the southwest-trending Grenville front truncates several Archean–Early Proterozoic structural provinces (Fig. 1). The parautochthonous Grenville front tectonic zone and the northwest Central Gneiss belt contain reworked equivalent rocks of these older provinces (Rivers et al., 1989). The rocks were displaced northwestward on crustal-scale, relatively low angle, ductile

Figure 1. Simplified tectonic map of eastern Great Lakes region modified after Carter and Easton (1990). Patterns in Grenville province: CGB—Central Gneiss belt, CMB—Central Metasedimentary belt, BT—Bancroft terrane, FT—Frontenac terrane, GRP—Great Plains province, MCR—Midcontinent rift, SP—Southern province, and ET—Elzevir terrane. GF—Grenville front; GFTZ—Grenville front tectonic zone. Dash-dot lines and question marks indicate southward extension of Grenvillian structures beneath Paleozoic cover. Box outlines study area of western CMB boundary zone in Lakes Erie and Ontario. Dashed lines and circles show locations of deep seismic reflection profiles: 1—Green et al. (1988), 2—Pratt et al. (1989), and 3—Forsyth et al. (1991). Dotted line indicates north limit of Paleozoic cover.

thrust zones, including the front (Green et al., 1988). Rocks in this region exhibit upper amphibolite to granulite facies metamorphism, and geobarometry suggests that as much as 30 km of upper crust has been removed in places (Anovitz and Essene, 1990).

Adjacent to the study area, the Grenville orogen comprises the southeast Central Gneiss belt of pre-Grenvillian polycyclic metamorphic rocks (>1.35 Ga) and the structurally overlying Central Metasedimentary belt, which contains metasupracrustal and plutonic rocks (<1.3 Ga) affected only by Grenvillian orogenesis. The latter belt in Ontario has been subdivided into three principal terranes (Bancroft, Elzevir, and Frontenac) characterized by different supracrustal assemblages, structures, metamorphism, and plutonism (Davidson, 1986). Units within this southeast region cannot be correlated with those on the foreland and are considered to be allochthonous relative to Grenvillian parautochthons and older provinces to the northwest (Rivers et al., 1989). Northwest thrusting ending at about 1060 Ma was followed by extension (Hanmer, 1988; van der Pluijm and Carlson, 1989).

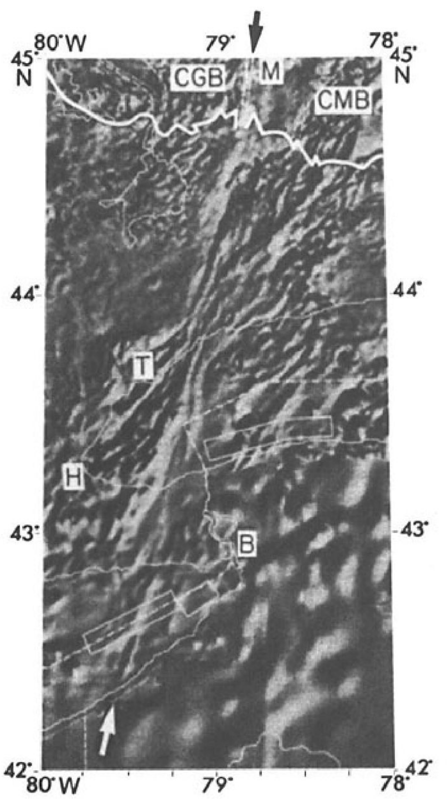


Figure 2. Shaded relief map of residual total magnetic field. Boxes indicate approximate line locations of proprietary seismic data. Arrows indicate strong linear anomaly trends from exposed margin of Central Metasedimentary belt (CMB) to Lakes Ontario and Erie. CGB = Central Gneiss belt. White line shows northern limit of Paleozoic cover. T—Toronto, B—Buffalo, H—Hamilton, M—Minden. General decrease in resolution of data in southern part of study area is due to increase in depth to basement and abrupt increase in data grid size south of Lake Erie (812 m grid in Lake Erie and 2 km grid to south).

The western boundary of the Central Metasedimentary belt is a broad zone of northwest-directed ductile shear, the present surface now exposing what took place at mid-crustal levels. Hanmer (1988) identified, immediately north of the Paleozoic cover, four overlapping major thrust sheets (each up to 4 km thick and 25 km in strike length) separated by regional southeast-dipping ductile shear zones as thick as 0.5 km. In this northern region, the Central Metasedimentary belt boundary zone of Hanmer (1988) extends the width of the Bancroft terrane (e.g., Davidson, 1986). Kinematic indicators show northwest-directed emplacement of the Metasedimentary belt over the Gneiss belt along zones with typical dips of 20°–30°.

The amplitudes of magnetic anomalies along the western boundary zone vary with lithology but are generally consistent in changing from high values over the Gneiss belt to lower values over the adjacent Metasedimentary belt. From this pattern we traced the boundary zone from its exposure along a series of linear anomalies to beneath western Lake Ontario and eastern Lake Erie. Although the western boundary zone is not uniquely defined by the potential field data, our interpretation of its location based on the new magnetic map (Fig. 2) is consistent with core samples from deep wells (Carter and Easton, 1990) and the seismic reflection data presented below.

Paleozoic sedimentary rocks increase in thickness south of the edge of the exposed Precambrian shield to ~0.5 km beneath western Lake Ontario, ~1.5 km beneath eastern Lake Erie, and as much as 10 km beneath the Appalachian basin of New York and Pennsylvania (Bailey Geological Services Ltd. and Cochrane, 1984; Rickard, 1973).

INDUSTRY SEISMIC REFLECTION DATA

The four east-west seismic profiles used in this study are from proprietary exploration surveys conducted in Lakes Ontario and Erie. In both lakes, 12- and 24-fold marine Vibroseis data were collected in 1971 and 60-fold airgun data were recorded in 1985. There were two profiles in Lake Erie <15 km apart and two profiles in Lake Ontario ~20 km apart. Surveys in the two lakes were separated by ~60 km (north-south), but the pairs of profiles overlap relative to north-trending geologic structures.

Some of the data presented here result from the application of extended correlation to increase the length of marine seismic records from 3 s to 8 s. Both the Vibroseis and airgun data were reprocessed with special focus on deep basement structures. Prestack and poststack multiple suppression, detailed velocity analyses, and enhancement of steep and conflicting dips were emphasized (prestack migration was used on the high-fold airgun data). Mild coherency filtering was applied to the stacked and migrated sections for data compression and display.

SEISMIC IMAGES

A composite 118-km-long east-west cross section, compiled from three overlapping seismic reflection profiles, is shown in Figure 3a. It extends to a depth of ~19 km in Lake Erie and as much as ~22 km in Lake Ontario. Reflector fabrics beneath the west end of Lake Ontario match closely those at the east end of Lake Erie, indicating continuity of deformational style; reflectors can be traced with confidence between seismic sections of different vintage. Our composite model features four main geologic or tectonic elements: the Gneiss belt, the Metasedimentary belt and its western boundary zone, a post-Grenville half graben, and undivided Paleozoic sedimentary rocks. The diffractive and discontinuous character of seismic events recorded within the Gneiss belt of Figure 3 contrasts with the more continuous features imaged within the Metasedimentary belt and its western boundary zone. Farther west, the Central Gneiss belt is represented by relatively chaotic reflection patterns (e.g., Green et al., 1988) and by west-dipping fabrics that may correlate with west-dipping reflections observed on COCORP's Ohio lines (Pratt et al., 1989; Culotta et al., 1990). Prominent east-dipping, deep reflectors within the Gneiss belt (distances of 0–10 km; Fig. 3) may represent a terrane boundary (e.g., the Allochthon boundary thrust of Rivers et al., 1989).

The western boundary zone is characterized by prominent east-dipping reflection zones that are either planar or listric at depth. We interpret many of these reflections as ductile faults bounding imbricate thrust sheets (e.g., I and II in Fig. 3b). On the basis of the southward extrapolation of basement rocks from the aeromagnetic map, the most western of the reflection zones (A in Fig. 4a) probably represents the fundamental suture of junction between allochthonous rocks of the Central Gneiss and Central Metasedimentary belts. It maintains an ~30° easterly dip from beneath the Paleozoic cover to ~10 km depth, whereupon it appears to flatten into a decollement extending to ~22 km depth. Gneiss belt rocks thus extend for 50–75 km beneath a thickening stack of Metasedimentary belt rocks.

Many of the prominent planar and listric reflections, both in the western boundary zone and interior to the Central Metasedimentary belt, border or truncate large-scale curvilinear reflection bands (e.g., B in Fig. 4a) that appear to represent either a sequence of folds successively truncated by later east-dipping faults, or a sequence of ramp folds or ramp anticlines generated in the mid-crust during northwest-directed compression. The dimensions of thrust sheets beneath the lakes (thicknesses of 3–9 km and

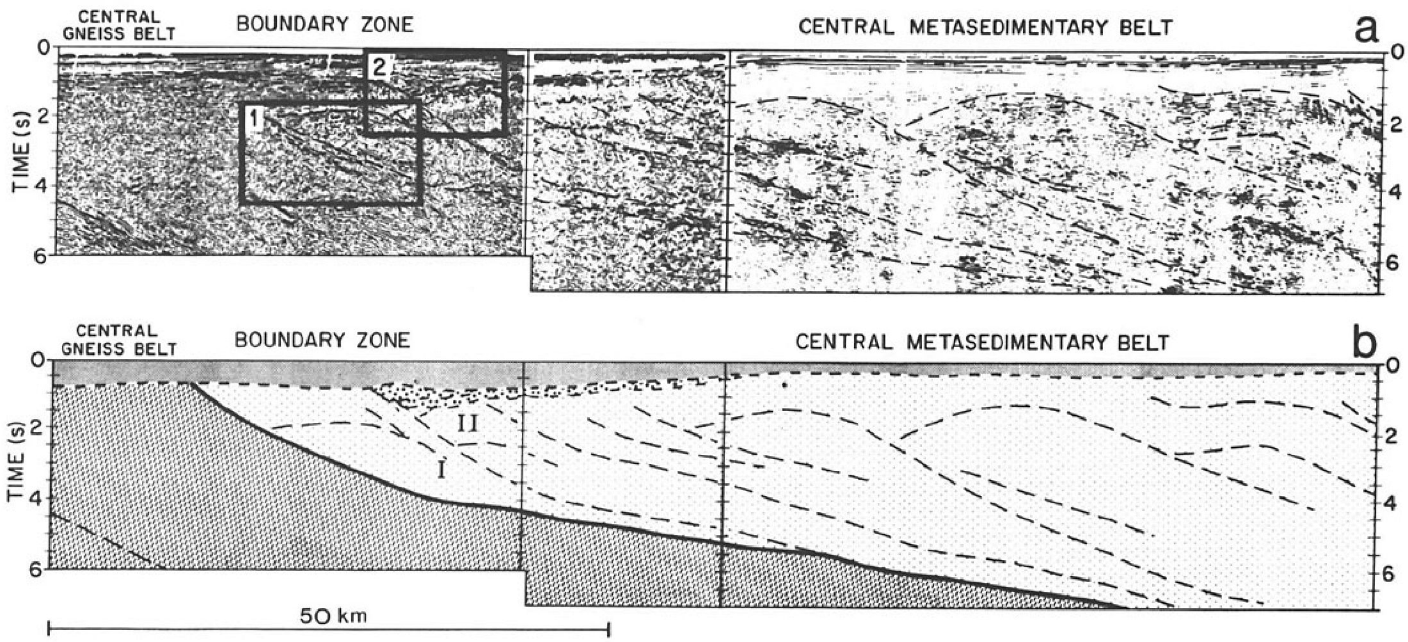


Figure 3. a: Composite seismic section across western Central Metasedimentary belt boundary zone in Lakes Erie and Ontario. Detailed seismic images from boundary zone (boxes 1 and 2) are shown in Figure 4. b: Interpretation showing principal crustal structures, post-Grenville basin, and undivided Paleozoic sedimentary cover, based on stacked and migrated seismic sections; seismic profiles parallel to those shown were incorporated in interpretation. I, II are thrust sheets.

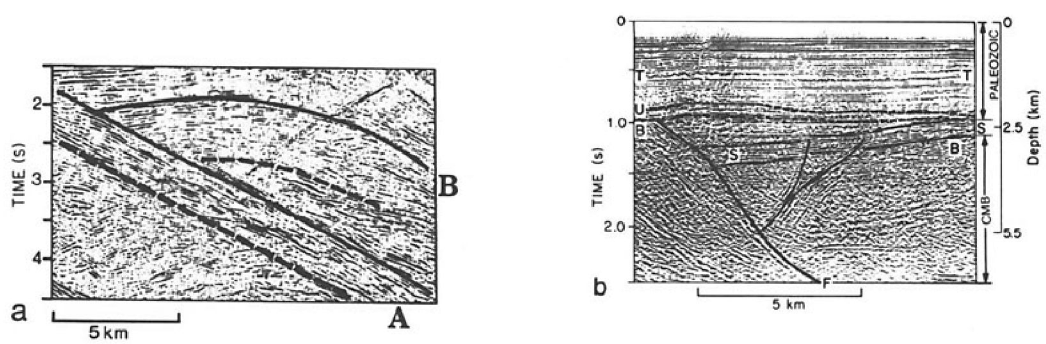


Figure 4. a: Interpreted seismic section from western Central Metasedimentary belt (CMB) boundary zone (box 1 in Fig. 3). Reflections A are 30° east-dipping events interpreted to be generated by mylonite zone along thrust fault separating Central Gneiss belt from Central Metasedimentary belt. Curvilinear reflection (B) is interpreted as deep-seated ramp fold or ramp anticline. b: Interpreted migrated section from within western boundary zone (box 2 in Fig. 3). Movement along presumed Grenvillian structures controlled development of half graben. S = Total layered sequence underlying Paleozoic sedimentary section; U = slightly disrupted package of sedimentary deposits immediately beneath early Paleozoic section; F = reverse fault between thrust sheets I and II (Fig. 3B), later reactivated as minor growth fault. Reflections from Trenton Group (T) and top of Precambrian basement (B) are seen at about 550 and 800 ms, respectively.

lengths of 5–20 km) are comparable to those mapped on the exposed shield by Hanmer (1988), but the folded or anticlinal nature of thrust sheets has yet to be documented in the field.

Reactivation of Basement Structures

There is evidence in the seismic sections for a post-Grenville layered sequence underlying the Paleozoic sedimentary section (S in Fig. 4b). This layered sequence extends from eastern Lake Erie at <0.5 km depth to ~4 km depth near the Central Metasedimentary belt margin, and was deposited in a local, fault-bounded half graben, which either formed during a late phase of extension associated with Mesoproterozoic Grenvillian orogenesis (e.g., during terminal collapse of the orogen) or was the result of pre-Appalachian rifting (Fisher, 1977). Extension leading to basin formation may have resulted in reversal of former thrust faults. Our interpretation shows west-dipping post-Grenville sediments abutting a steep, east-dipping fault (F in Fig. 4b). It appears that thrust sheet I (Fig. 3b) became welded to the Gneiss belt and was not reactivated during the late normal faulting. Most differential (normal) movement probably occurred along the former thrust fault F between sheets I and II. Note that the top of the Trenton Group, a Middle Ordovician shale-limestone assemblage and an important marker horizon for exploration seismic studies, is not disturbed significantly, indicating that this region has remained relatively stable since Ordovician time.

DISCUSSION AND SUMMARY

Reprocessed marine seismic reflection profiles have resolved important features of the crust underlying the Mesoproterozoic Grenville orogen, including the junction between the pre-Grenvillian metamorphic rocks of the Central Gneiss belt and metasupracrustal and plutonic units of the Central Metasedimentary belt. Seismic data across the western boundary zone of the latter belt reveal a pattern of reflectors that dip 15° to 30° with both planar and listric geometries that can be traced to depths of at least 22 km. We interpret the reflections as originating from thrust faults that sole into a gently east dipping decollement that is the floor of a deep, crustal-scale duplex. The roof of the duplex, which lies along the crests of the ramp folds or ramp anticlines, may crop out as one of the major terrane boundaries east of the survey area (e.g., the Elzevir-Frontenac boundary or the Carthage-Colton mylonite zone). The duplex may have a more complicated geometry than suggested here, and it may have been active during several periods of Grenvillian orogenesis. In at least two areas (e.g., the western boundary zone and the east end of the profile), the vertical stacking of thrust sheets is consistent with coeval or later out-of-sequence thrust faulting of the type described by Hanmer (1988).

These imbricated and folded structures, represented by these seismic images, that continue into the mid-crust resemble structures seen in the deeply eroded regions of much younger orogens such as the Canadian Cordillera (e.g., Cook et al., 1992). They may, therefore, be a general characteristic of orogenic belts. The new seismic images support tectonic models involving lateral growth of the Canadian Shield during the Grenvillian orogeny by accretion of the Metasedimentary belt as a composite assemblage that was thrust over older rocks of the continental margin (Davidson, 1986; Windley, 1986).

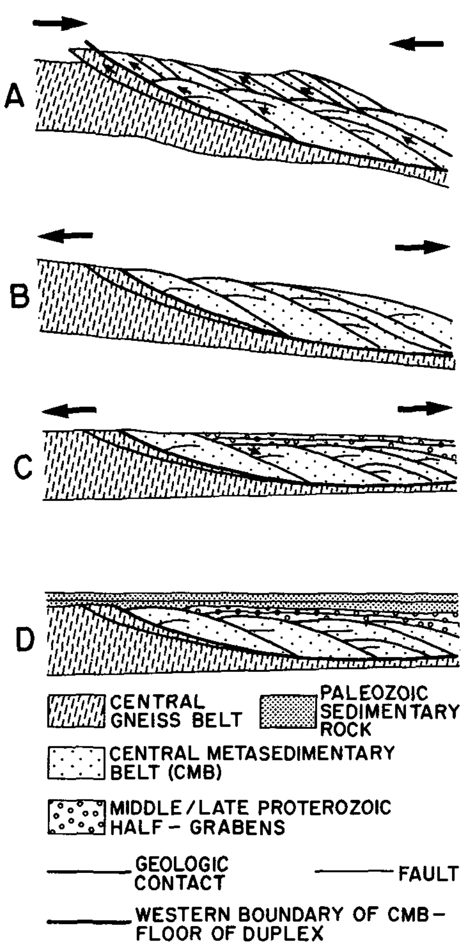


Figure 5. Cartoon illustrating tectonic development of western boundary zone. A: Terrane boundary was created by collision of southeastern Gneiss belt with Metasedimentary belt. There is multiple thrusting of allochthons on Gneiss belt and formation of deep crustal-scale duplex and upper crustal zones of imbrication. B: Uplift and erosion of upper crustal layer (early collapse phase of Grenvillian orogeny). C: Extension and formation by normal faulting of asymmetric basin (either terminal collapse of Grenville orogen or initiation of pre-Appalachian Iapetus continental margin). D: Late Paleozoic sediments deposited in Appalachian foreland basin.

Figure 5 summarizes the tectonic development of the western boundary zone from the Mesoproterozoic. The tectonic model starts with supracrustal and plutonic rocks either separated from the Gneiss belt by an oceanic or back-arc basin or bordering a passive margin. Alternative models may include either an east-dipping (Corriveau, 1990) or west-dipping (Hanmer and McEachern, 1992) subduction zone; the direction of subduction is not critical to the model, only convergence between the two belts is required. Multiple thrusting of allochthonous sheets over the Gneiss belt occurred along the southeast-dipping western boundary zone, which at depth becomes the floor of a deep, crustal-scale duplex (A in Fig. 5). The lower part of the model is derived from seismic reflection data, and the generalized geometry of the upper part is similar to evolutionary models proposed for the internal metamorphic zones of the European Alps and Canadian Cordillera (e.g., Mattauer et al., 1983; Cook et al., 1992). The nature of rock units above the mid-crustal duplex during stage A is unknown. Uplift and almost complete erosion of the upper Grenvillian crust preceded the formation of one or more small half grabens (stages B and C). These half grabens may represent a very late period of post-orogenic collapse following Grenvillian tectonism, or they may be the result of pre-Appalachian rifting. Finally, Paleozoic sediments were deposited in the Appalachian foreland basin.

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REFERENCES CITED

Annovitz, L.M., and Essene, E.J., 1990, Thermobarometry and pressure-temperature paths in the Grenville Province of Ontario: Journal of Petrology, v. 31, p. 197–241.

Bailey Geological Services Ltd., and Cochrane, R.O., 1984, Evaluation of the conventional and potential oil and gas reserves of the Cambrian of Ontario: Ontario Geological Survey Open File Report 5499.

Braile, L.W., Hinze, W.J., Keller, G.R., and Lidiak, E.G., 1982, An ancient rift complex and its relation to contemporary seismicity in the New Madrid seismic zone: Tectonics, v. 1, p. 225–237.

Carter, T.R., and Easton, M.S., 1990, Extension of Grenville basement beneath southwestern Ontario: Lithology and tectonic subdivisions, *in* Carter, T.R., ed., Subsurface geology of southwestern Ontario: A core workshop: London, Ontario Petroleum Institute, p. 9–28.

Cook, F.A., and nine others, 1992, LITHOPROBE crustal reflection cross section of the Southern Canadian Cordillera. 1, Foreland thrust and fold belt to Fraser River fault: Tectonics, v. 11, p. 12–35.

Corriveau, L., 1990, Proterozoic subduction and terrane amalgamation in the southwestern Grenville province, Canada: Evidence from ultrapotassic to shoshonitic plutonism: Geology, v. 18, p. 614–617.

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.

Davidson, A., 1986, New interpretations in the southwestern Grenville Province, *in* Moore, J.M., et al., eds., The Grenville Province: Geological Association of Canada Special Paper 31, p. 61–74.

Fisher, D.W., 1977, Correlation of Hadrynian, Cambrian and Ordovician rocks in New York State: Albany, New York State Map and Chart Series 25, 75 p.

Forsyth, D.A., Milkereit, B., Hinze, W.J., Mereu, R.F., and Asmis, H., 1991, Crustal structures from the southwestern Grenville Province: A progress report on the processing and interpretation of reflection data in lakes Ontario, Erie and Huron, *in* Current research, Part C: Geological Survey of Canada Paper 91-1C, p. 71–76.

Green, A.G., and nine others, 1988, Crustal structure of the Grenville front and adjacent terranes: Geology, v. 16, p. 788–792.

Hanmer, S., 1988, Ductile thrusting at mid-crustal level, southwestern Grenville Province: Canadian Journal of Earth Sciences, v. 25, p. 1049–1059.

Hanmer, S., and McEachern, S., 1992, Kinematical and rheological evolution of a crustal-scale ductile thrust zone, Central Metasedimentary Belt, Grenville orogen, Ontario: Canadian Journal of Earth Sciences (in press).

Mattauer, M., Collet, B., and Van den Driessche, J., 1983, Alpine model for the internal metamorphic zones of the North American Cordillera: Geology, v. 11, p. 11–15.

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.

Rickard, L.V., 1973, Stratigraphy and structure of the subsurface Cambrian and Ordovician carbonates of New York: New York State Museum and Science Service Map and Chart Series 18, 26 p.

Rivers, T., Martignole, J., Gower, C.F., and Davidson, A., 1989, New tectonic divisions of the Grenville Province, southeast Canadian Shield: Tectonics, v. 8, p. 63–84.

van der Pluijm, B.A., and Carlson, K.A., 1989, Extension in the Central Metasedimentary Belt of the Ontario Grenville: Timing and tectonic significance: Geology, v. 17, p. 161–164.

Windley, B.F., 1986, Comparative tectonics of the western Grenville and the western Himalaya, *in* Moore, J.M., et al., eds., The Grenville Province: Geological Association of Canada Special Paper 31, p. 341–384.

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