Seismic images of a tectonic subdivision of the Grenville Orogen beneath lakes Ontario and Erie[1]

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New seismic data from marine air-gun and Vibroseis profiles in Lake Ontario and Lake Erie provide images of subhorizontal Phanerozoic sediments underlain by a remarkable series of easterly dipping reflections that extends from the crystalline basement to the lower crust. These reflections are interpreted as structural features of crustal-scale subdivisions within the Grenville Orogen. Broadly deformed, imbricated, and overlapping thrust sheets within the western Central Metasedimentary Belt are succeeded to the west by a complex zone of easterly dipping, apparent thrust faults that are interpreted as a southwest subsurface extension of the boundary zone between the Central Metasedimentary Belt and the Central Gneiss Belt. The interpreted Central Metasedimentary Belt boundary zone has a characteristic magnetic anomaly that provides a link from the adjacent ends of lakes Ontario and Erie to structures exposed 150 km to the north. Less reflective, west-dipping events are interpreted as structures within the eastern Central Gneiss Belt. The seismic interpretation augments current tectonic models that suggest the exposed ductile structures formed at depth as a result of crustal shortening along northwest-verging thrust faults. Relatively shallow reflections across the boundary region suggest local, Late Proterozoic extensional troughs containing post-Grenville sediments, preserved possibly as a result of pre-Paleozoic reactivation of basement structures.

De nouvelles données sismiques, tirées de profils marins obtenus par les méthodes de canon à air et Vibroseis, pour le lac Ontario et le lac Érié, fournissent des images de sédiments subhorizontaux phanérozoïques sus-jacents à une série clairement exprimée de réflexions à pendage vers l'est d'un socle cristallin qui s'étend jusqu'à la croûte inférieure. Ces réflexions sont interprétées comme les représentations structurales de subdivisions à échelle crustale dans l'orogène de Grenville. Les nappes de charriage chevauchantes, fortement déformées et imbriquées dans la Zone métasédimentaire centrale occidentale sont suivies à l'ouest par une bande complexe de failles apparentes imbriquées à pendage vers l'est, interprétée comme l'extension sud-ouest, en subsurface, de la bordure qui sépare la Zone métasédimentaire centrale de la Zone de gneiss centrale. Cette bordure interprétée de la Zone métasédimentaire centrale est caractérisée par une anomalie magnétique qui relie les extrémités des lacs Ontario et Érié aux structures exposées à 150 km au nord. Des réflecteurs à pendage ouest, cependant moins clairement définis, sont interprétés comme des représentations structurales intérieures à la Zone de gneiss centrale orientale. L'interprétation sismique plaide en faveur des modèles tectoniques courants qui suggèrent que les structures ductiles exposées se sont formées en profondeur et qu'elles résultent d'un racourcissement crustal développé le long de failles de chevauchement de vergence nord-ouest. Des réflexions de niveaux relativement peu profonds traversant la région de la bordure suggèrent la présence de fossés tectoniques locaux, créés par des évènements de distension au Protérozoïque tardif, et contenant des sédiments postgrenvilliens, préservés possiblement grâce à une réactivation antépaléozoïque des structures du socle.

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Introduction

This paper integrates new seismic constraints with magnetic and borehole data to interpret both shallow and deep crustal structure within the southern Grenville Orogen. Figure 1 shows the study area in relation to surveys across (1) the Grenville Front Tectonic Zone in northern Lake Huron (Green et al. 1988; Milkereit et al. 1990), (2) the Michigan Basin (Zhu and Brown 1986), (3) Ohio (Pratt et al. 1989), and (4) northern New York State (Brown et al. 1983). Open triangles in Fig. 1 indicate Great Lakes surveys described in Forsyth et al. (1991, 1994), and closed circles indicate shallow surveys reported in Beardsley and Cable (1983). Little is known about Grenville basement structures in the eastern Great Lakes area (Pakiser and Mooney 1989). Deep seismic profiles in northern New York State (Brown et al. 1983) have provided information on the structure of the eastern Grenville Orogen, but the general lack of geological constraints for deep seismic data has enabled only rather speculative tectonic models (e.g., Culotta et al. 1990). The data presented here come from lakes Erie and Ontario where geopotential maps strongly suggest the continuity of Grenvillian structural trends beneath a southward-thickening Paleozoic section (Forsyth et al. 1992). The nature of both the Paleozoic–Precambrian unconformity and underlying structure are poorly known (e.g., Bailey Geological Services Ltd. and Cochrane 1984) from a small number of boreholes and even fewer cored samples. Attitudes of basement structures, the sense and timing of possible rejuvenation,

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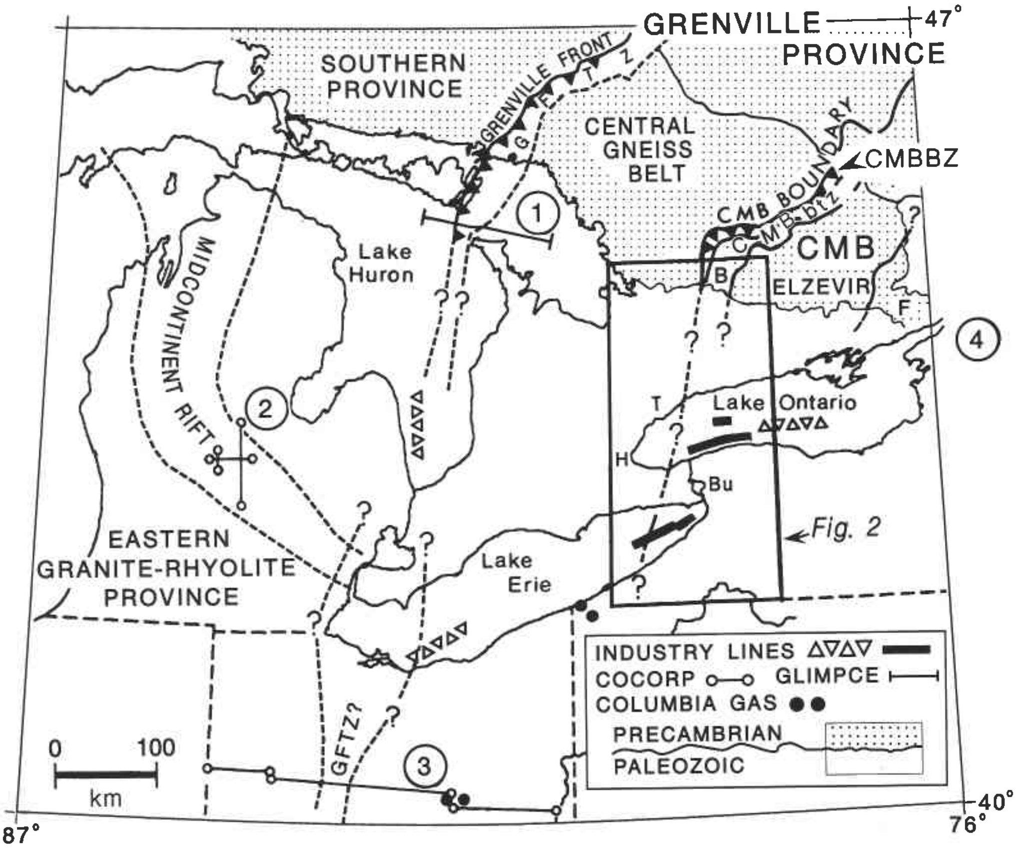

FIG. 1. Tectonic element map of the Great Lakes area. Box denotes study area. Symbols refer to seismic profiles cited in text. Circled numbers refer to seismic surveys described in the text. B, Bancroft terrane; F, Frontenac terrane; T, Toronto; H, Hamilton; Bu, Buffalo; GFTZ, Grenville Front Tectonic Zone; CMB, Central Metasedimentary Belt; CMB btz, Central Metasedimentary Belt boundary tectonic zone. CMB boundary to Lake Ontario after Carter and Easton (1990).

and their relation to potential field anomalies are also uncertain. The study area includes the cities of Toronto, Hamilton, and Buffalo, and is one of the more densely populated areas in North America.

The following sections describe recent results from the nearby exposed Grenville Province, the relationship of mapped geology and seismically imaged features to potential field anomalies, and borehole results from south of the Canadian Shield to constrain our interpretation of new deep seismic reflection images beneath western Lake Ontario and eastern Lake Erie (Fig. 1). The interpreted Precambrian tectonic divisions extend and augment recent models of the central Grenville Orogen (Davidson 1986; Mezger et al. 1991; Hanmer and McEachern 1992).

Regional setting

Paleozoic section

The flat-lying Paleozoic strata, although jointed and locally offset, are essentially undeformed and locally covered by thick Pleistocene deposits. Borehole and seismic data indicate that the Paleozoic succession thickens southward to about 500 m beneath western Lake Ontario, 900 m beneath the Niagara Peninsula, 1500 m beneath eastern Lake Erie, and up to 10 km in the Appalachian Basin of New York and Pennsylvania (Bailey Geological Services Ltd. and Cochrane 1984; Pohn and Coleman 1991). Limited borehole data between the adjacent ends of lakes Ontario and Erie indicate possible Precambrian basement material similar to Grenville rocks exposed some 150 km to the north. South of eastern Lake Erie, Beardsley and Cable (1983) present seismic evidence for east-dipping structure underlying relatively undisturbed Paleozoic cover in northwest Pennsylvania and eastern Ohio. Wagner (1976) and Harper (1989) suggest that Paleozoic basin development in northern Pennsylvania has been affected by growth faulting originating in lower or sub-Paleozoic rocks.

Southern Grenville Province

The Precambrian basement beneath the Great Lakes is part of the North American Mid-Proterozoic Grenville Orogen extending from Labrador southwest to Texas and Mexico; the exposed part within the Canadian Shield is known as the Grenville Province. Some 300 km northwest of the study area, the margin of the Grenville Province is marked by a prominent, southwest-trending structural lineament, the Grenville Front, which truncates older structural provinces to the northwest. In Fig. 1 these young progressively southwestward and are (*i*) the Southern Province, in Ontario containing east–west-folded, Early Proterozoic supracrustal rocks (Huron Supergroup), and in the Lake Superior region of the United States, younger supracrustal rocks deformed during the Penokean orogeny (1.9–1.83 Ga.); (*ii*) the eastern Central Plains Province, characterized by 1.75–1.65 Ga granitic and volcanic igneous activity equated with the Yavapai–Mazatzal orogens of the western United States, and (*iii*) the midcontinent granite–rhyolite province (1.48–1.35 Ga). The last two of these provinces south of the Penokean foldbelt are extrapolated east to the Grenville Front beneath the Paleozoic Michigan Basin, which also covers the eastern extension of the Midcontinent Rift.

Within the Grenville Province, the parautochthonous belt (Rivers et al. 1989) contains reworked equivalent rocks of all four provinces, displaced northwestward on crustal-scale, relatively low angle, ductile thrust zones, including the Grenville Front (Green et al. 1988). These rocks form Wynne-Edwards' (1972) Grenville Front Tectonic Zone and underly the northwestern Central Gneiss Belt. Adjacent to the study area, the Central Gneiss Belt, a polycyclic belt containing pre-Grenvillian metamorphic rocks (>1.35 Ga), and, structurally above this, the Central Metasedimentary Belt (CMB), a monocyclic belt containing metasupracrustal and plutonic rocks (>1.3 Ga), have been affected only by the Grenville orogenic cycle (Rivers et al. 1989).

Southeastern Central Gneiss Belt

The southeastern Central Gneiss Belt contains rocks that cannot be correlated with those outside the Grenville Province and is considered allochthonous with respect to the Grenville parautochthon and the older cratonic provinces to the northwest (Rivers et al. 1989). Central Gneiss Belt rocks are internally dissected and overlie the parautochthon on shallowly southeast-dipping ductile thrust zones. Folding, during or following thrust slice emplacement, has produced convolute surface traces of these zones and locally the parautochthon appears as tectonic windows within the allochthonous part of the Central Gneiss Belt. The Central Gneiss Belt adjacent to the CMB boundary is itself sliced by high-strain zones. For example, west of Minden (Fig. 2), a major shear zone, decorated with tectonic inclusions of gneissic anorthosite, diverges southwestward from the highly strained rocks that floor the lowest (Redstone) crystalline thrust slice (Hanmer 1989). This zone, originally defined as the lower margin of the CMB boundary (Davidson et al. 1984), is now interpreted as the base of a domain within the Central Gneiss Belt (Easton 1986). Similarly oriented divergences appear in the magnetic anomaly pattern south of the Paleozoic unconformity (Fig. 2).

Rocks of the eastern Central Gneiss Belt exhibit upper-amphibolite- to granulite-facies metamorphism; geobarometry suggests that they were at one time buried at depths between 30 and 40 km (Anovitz and Essene 1990, their Fig. 8). Apart from minor gabbro and pegmatite, rocks in the Central Gneiss Belt are older than ~1.3 Ga and include supracrustal gneisses formed before subsequent Grenvillian orogeny. Thus, Rivers et al. (1989) refer to the southeast part of the Central Gneiss Belt as the allocthonous polycyclic belt. Carter and Easton (1990) have inferred Central Gneiss Belt subdivisions beneath Paleozoic cover to the south from borehole and potential field data.

Central Metasedimentary Belt

At the limit of Paleozoic cover north of the study area (Fig. 1), the CMB is divided (Davidson 1986) into three principal terranes, namely Bancroft, Elzevir, and Frontenac, all containing tracts of marble that distinguish the CMB from the structurally underlying Central Gneiss Belt. Apart from marble in the supracrustal rocks of the CMB (Grenville Supergroup of Wynne-Edwards 1972), all three terranes appear to differ significantly in supracrustal assemblage, structure, age, metamorphism, and type of plutonic rocks. A recent summary of the CMB is found in Easton (1992).

Exposed Central Metasedimentary Belt – Central Gneiss Belt boundary

The boundary was first thought to be of tectonic origin by Barlow (1899) and Adams and Barlow (1910). During the 1980's, the interpretations and acronyms assigned to the boundary evolved rapidly from the "coarse clastic sequence" of Schwerdtner and Lumbers (1980) through the "CMB boundary tectonic zone" (CMBBTZ of Culshaw et al. 1983), the "CMB boundary zone" (Hanmer and Ciesielski 1984), to the "CMBBZ" (Davidson 1986 and later papers). Beneath exposure, White et al. (1994) show the combined CMBBZ and adjacent Bancroft terrane (Fig. 1) form a major shallowly southeast-dipping complex, in general agreement with the CMB boundary thrust zone or "CMBbtz" of Hanmer and McEachern (1992). The CMB boundary thrust zone separates the Central Gneiss Belt from the overlying supracrustal assemblage and Grenvillian-age intrusions of Elzevir terrane to the southeast.

Kinematic evidence in layered quartzofeldspathic tectonites of the lower CMB boundary thrust zone indicates thrusting to the northwest (Hanmer 1988). U–Pb zircon ages from syntectonic pegmatite and granite sheets within the zone suggest a major period of thrusting at ~1060 Ma (van Breemen and Hanmer 1986), but earlier deformation, ca. 1190 Ma, has also been identified (McEachern and van Breemen 1993). Apart from calcite and dolomite marble, supracrustal rocks in the boundary thrust zone include pelitic and rusty calc-silicate gneiss and local quartzite; unequivocal metavolcanic rocks are absent. Nepheline and alkaline gneisses of disputed origin, either metaplutonic rocks or metasomatites from evaporitic successions, occur near the structural top of Bancroft terrane.

Rocks now exposed present relationships produced at middle to lower crustal depths during deformational cycles of the Grenville orogeny in contrast with structures formed in an upper crustal fold and thrust belt. For example, the CMB boundary thrust zone incorporates a number of large crystalline sheets or pods, but lacks narrowly defined thrust faults normally found near the surface. In scale, the CMB boundary thrust zone adjacent to the study area appears to be up to about 10 km thick (McEachern and van Breemen 1993) and contains southeast-dipping crystalline thrust sheets with typical dimensions of 4–5 km enclosed in anastomosing zones of marble and silicate tectonites reaching ~500 m in thickness (Hanmer 1988). The carbonate rocks, represented by marble tectonic breccia along with silicate tectonites, have provided the main ductile medium within which these sheets have been stacked northwestward. Highly strained rocks locally exhibiting similar kinematics occur throughout the exposed CMB boundary thrust zone, inhomogeneously distributed about large, lenticular sheets of quartzofeldspathic and amphibolitic gneiss (Hanmer 1989) that may represent either reworked Central Gneiss Belt gneisses and (or) a separate crystalline basement to the CMB supracrustal rocks (in situ basement to the Grenville Supergroup has yet to be identified). The boundary with the Central Gneiss Belt has been defined as a zone where the boundary thrust zone cuts across deformation structures in the underlying Central Gneiss Belt (Hanmer and McEachern 1992, p. 1780). We shall use this definition and similarities to seismic images of the CMB boundary thrust zone (White et al. 1994) and to attitudes and dimensions of the exposed CMB boundary thrust zone in the following seismic interpretation of the Paleozoic-covered CMB boundary zone to the south.

Evidence for extension

Extension has been recognized in several places within the CMB boundary thrust zone (e.g., van der Pluijm and Carlson 1989; Carlson et al. 1990; Cosca et al. 1991; Hanmer and

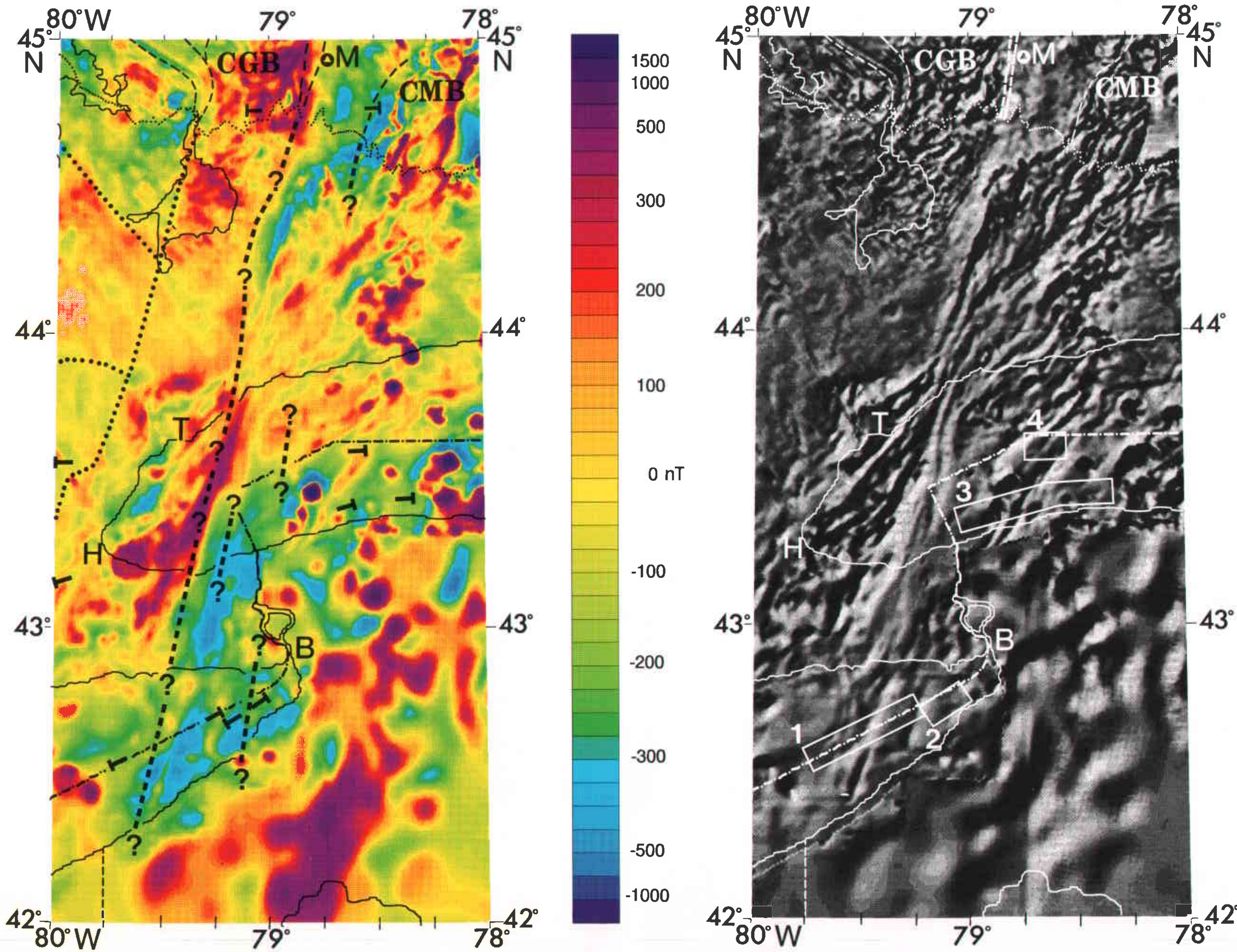

FIG. 2. (*a*) Residual total magnetic field (International Geomagnetic Reference Field 1975 removed). (*b*) Shaded relief image of (*a*) illuminated from an apparent sun to the southeast. Rectangles 1, 2, 3, and 4 are seismic profile segments for Figs. 3, 4, 5, and 6, respectively. The southwest extension of the CMB boundary zone is based on seismic calibration of magnetic data in lakes Ontario and Erie. CMB boundary to Lake Ontario and dotted subdivisions after Carter and Easton (1990). ET, Elzevir terrane. ⊢, end of magnetic profiles (Fig. 3). Fine dotted line shows northern limit of Paleozoic cover. Dashed lines indicate magnetic trends coincident with interpreted boundary zone limits. B, Buffalo; M, Minden. Other abbreviations as in Fig. 1.

TABLE 1. Chronology of tectonic events along the CMB boundary in Ontario

Event	Time (Ga)	Reference
Northwest-directed thrusting		
Northeast CMB btz	1.23−1.19	Hanmer and McEachern 1992
Northeast and southwest CMB btz	1.08−1.05	van Breemen and Hanmer 1986 Hanmer and McEachern 1992
Peak metamorphism	Prior to 1.04	Hanmer and McEachern 1992
Southwest CMB btz thrusting	Continues to ca. 1025 Ma	Mezger et al. 1991
Extension (Bancroft shear zone)	1.04 to ca. 1.01−0.94	van der Pluijm and Carlson 1989
Exhumation of lower crust	0.94−0.7	Cosca et al. 1991
Extension (western Lake Ontario − eastern Lake Erie	<0.94	This work

McEachern 1992). Immediately north of the study area, relatively low temperature extensional mylonites, developed mainly in carbonate and syenitic rocks, form a relatively narrow zone (<1 km) near the top of the Bancroft terrane. Thermochronology data from retrograde marble mylonite suggest extension continued along this zone until 935−1010 Ma (van der Pluijm and Carlson 1989), near the close of the Grenville orogeny. The following seismic interpretation suggests post-Grenville extension within the southwest extension of the CMB boundary zone. A chronology of tectonic events along the CMB boundary in Ontario is summarized in Table 1.

Subsurface continuation of the CMB boundary zone

In addition to structural similarity, the exposed components (CMB boundary zone of Davidson 1986, and Bancroft terrane) are not separable by the magnetic anomaly pattern. In the area of the seismic lines, no sub-Paleozoic constraints are available to distinguish subdivisions of the boundary zone or rocks of Elzevir terrane to the east. Immediately north of the Paleozoic cover, the surface width of the boundary thrust zone varies from a few kilometres to about 45 km as a function of dip and dimensions of incorporated crustal slices. The variations in local structural style and lithology are reflected in the associated magnetic anomaly pattern (Fig. 2). Near the southern edge of the exposed CMB boundary (Figs. 2 and 3) the most positive magnetic anomalies correlate with mapped mafic and syenogranite gneiss in the Central Gneiss Belt (Easton 1988). Farther north, the CMB boundary coincides with a transition from more positive anomalies over an irregular granitic gneiss of the Central Gneiss Belt to negative magnetic anomalies over the Redstone thrust sheet (Hanmer 1989). Without structural constraints, individual magnetic anomalies cannot be used to uniquely distinguish elements of the boundary zone nor the boundaries with adjacent terranes. In summary, the magnetic anomaly amplitudes vary with the lithology of the rocks along the western edge of the exposed CMB boundary but are consistent in changing from more positive values over the Central Gneiss Belt to lower values over the CMB.

The southwest continuity of magnetic anomalies from exposed lithological units across areas of nonmagnetic Paleozoic cover (Forsyth et al. 1992) indicates that the anomaly sources are in the underlying Precambrian rocks. In addition, two-dimensional models of magnetic anomalies within the CMB suggest that short-wavelength magnetic anomalies are due to sources at depths less than about 5 km (Newitt and Dawson 1980). In the study area, we suggest that the more positive magnetic anomalies west of the CMB boundary can be attributed to generally higher average magnetic susceptibility of Central Gneiss Belt rocks. In the following sections we interpret similarities between (*i*) mapped geological attitudes and consistent apparent seismic reflection dips from four different seismic lines (Fig. 2) and (*ii*) geological trends and zones of seismic reflections linked by the trend and nature of magnetic anomalies, as evidence for the southerly continuation of the CMB boundary zone beneath Lake Ontario and eastern Lake Erie (see also Carter and Easton 1990).

Post-Grenvillian tectonism

There is little evidence of significant tectonic adjustments affecting the study area between about 900 Ma and the deposition of Cambrian sands. The Late Proterozoic − early Paleozoic tectonic history of the southern study area is linked to the evolution of the Appalachian Orogen (e.g., Rankin et al. 1989) as clastics and carbonates covered the continental shelf of a proto-Atlantic formed by rifting. The thickness of Cambrian sediments and the depth to Precambrian basement increases southward, with Cambro-Ordovician units around Lake Ontario reaching a thickness of about 500 m. Although adjustment of Precambrian basement structures may have affected local basin development (Wagner 1976), the Cambro-Ordovician rocks escaped significant Appalachian deformation and lie unconformably on Precambrian basement. South and west of the study area, the Paleozoic section includes hydrocarbon-bearing Silurian and Devonian sediments. Finally, mild antiformal reflections in the Lake Erie seismic data described below may indicate weak compression associated with the closing of the Iapetus Ocean during the Taconic orogeny.

Images of the CMB boundary

Seismic data processing−resolution

The seismic data were recorded on proprietary marine surveys in the eastern Great Lakes. In 1971, 12- and 24-fold marine Vibroseis data and in 1985, 60-fold marine air-gun data were collected. Part of the interpretation presented here is based on the first use of extended correlation of marine Vibroseis data (Milkereit and Forsyth 1992) in the study of deep crustal structure. The marine Vibroseis data were reprocessed using the self-truncated sweep correlation technique to extend seismic records to 8 s two-way time. Both air-gun and Vibroseis data were reprocessed to clarify deep basement structure by applying pre- and post-stack multiple suppression, detailed velocity analysis, and enhancement of steep and conflicting dips (DMO processing). Subsequently, mild coherency filtering (Milkereit and Spencer 1989) was applied to stacked and migrated data for compression and display.

Several of the strong, dipping reflections are interpreted as

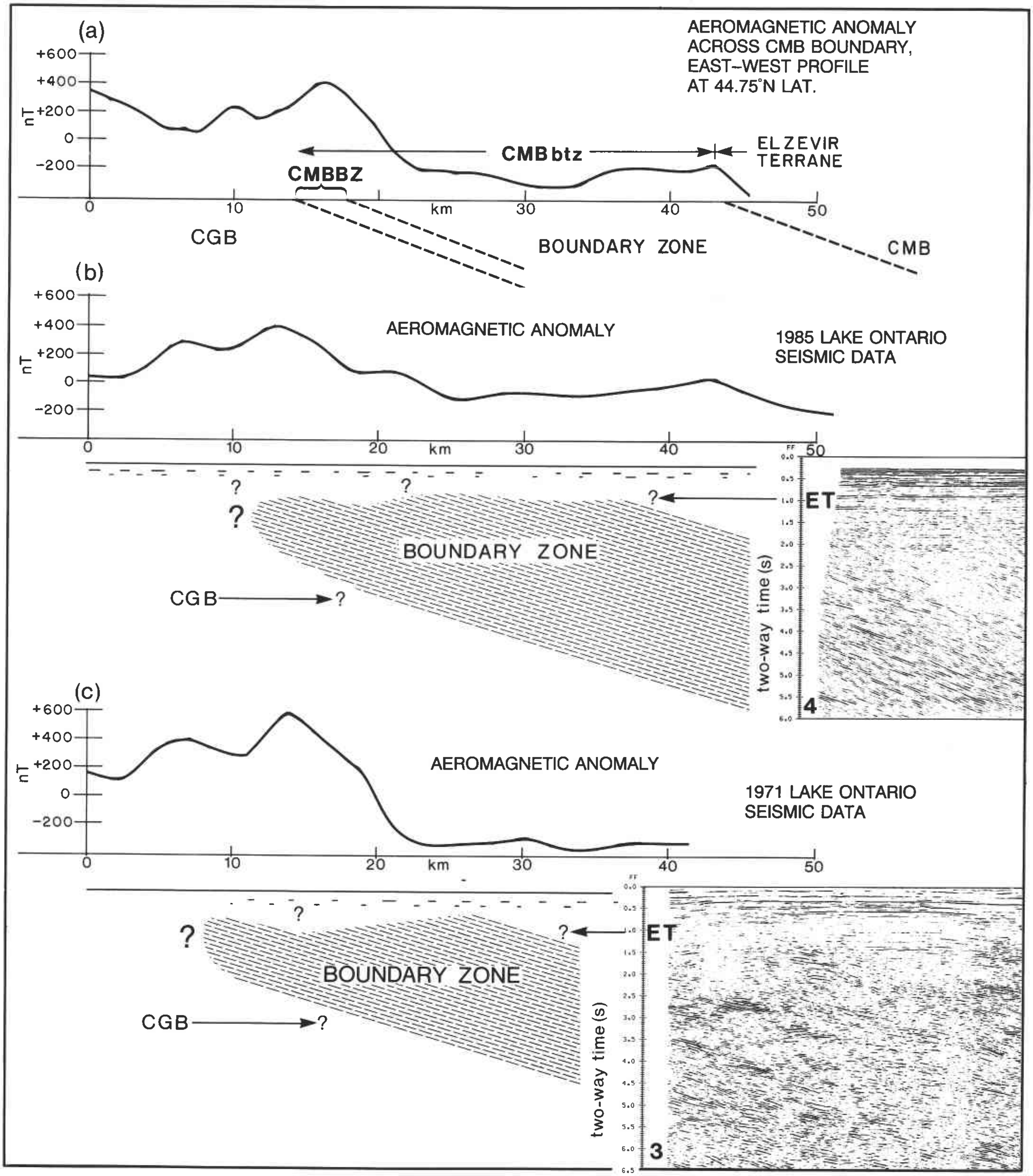

FIG. 3. Magnetic profiles with mapped and interpreted positions of the CMB boundary. Note the relationship of potential field anomalies to (*a*) exposed position at 44.75°N and (*b* and *c*) structure projected to subcrop depth ~15 km west of seismic profiles 3 and 4 (Fig. 2) and variation in reflection complexity of east-dipping boundary zone between (*b*) and (*c*).

thrust zones by analogy to synthetic reflections computed for mylonite zones. Jones and Nur (1984) and Hurich and Smithson (1987) have examined the causes of reflections from mylonites in exhumed ductile shear zones and in crystalline rocks with compositional variations and metamorphic grades similar to those of Grenville rocks within and adjacent to the study area. For seismic data similar to this study, Hurich and Smithson (1987) showed that constructive interference and compositional changes are major factors in producing reflections that resolve layering on the order of 30–80 m, even though layers of different thicknesses may be present. Overall resolution will depend on background noise. We limit our interpretation to the major geometrical changes in reflection attitude and character (curvature and (or) amplitude) and to those features (e.g., structural strike and dip) supported by the exposed geology.

Seismic profiles in Lake Erie are separated by less than 15 km and converge to the northeast; diverging profiles in Lake Ontario are separated by approximately 20 km. The adjacent surveys in lakes Erie and Ontario are separated by about 60 km in a north–south direction, but the profiles overlap northeast-trending geological features based on the continuity of magnetic anomaly trends. The lines cross regional magnetic anomaly strike, and we suggest the similarity in seismic structures provides additional evidence of structural continuity along geological strike.

Magnetic anomalies and seismic data

Figure 3 shows three generally east–west magnetic profiles across the CMB boundary from where last exposed at the Paleozoic limit to profiles coincident with the seismic line segments 3 and 4 (Fig. 2) in western Lake Ontario. Near 44°45′N, the easterly dipping CMB boundary coincides with a west to east, positive to negative change in the magnetic field. In west-central Lake Ontario, a similar positive to negative change in magnetic field coincides with the position of a strongly reflective, east-dipping zone extrapolated from the end of the seismic section to subcrop depth beneath the lake (dashed pattern in Fig. 3*b*). Boundary-zone reflections have easterly apparent dips of about 20°. Although the change from subhorizontal and antiformal reflections to more linear reflections with easterly dips may indicate a change from Elzevir terrane rocks to structure with dips similar to those described for the exposed CMB boundary thrust zone, no geological calibration is available beneath the lake. The Precambrian–Paleozoic unconformity (obscured by multiples above approx. 1 s in Figs. 3*a* and 3*b*) is a poor reflector, probably due to minimal velocity contrast between Paleozoic and Precambrian rocks and a variable weathered zone coupled with topography along the unconformity.

To the southwest (Fig. 3*c*), an analogous change in magnetic anomaly coincides with the projected position (Fig. 2) of a similar change from subhorizontal, arcuate reflections to stronger reflections with easterly apparent dips of 15–20°. Easterly dips of 15–30° are measured within the exposed boundary zone (Hanmer 1988). Using the strike of magnetic anomalies as structural strike, the minor changes in apparent dips evident on the sections agree with the minor change in trend of the seismic lines relative to the magnetic trends. The subcrop projections of the proposed eastern edge of the CMB boundary zone beneath western Lake Ontario are indicated as short dashed lines following magnetic anomaly strike in Fig. 2. The western limit of the CMB boundary zone (dashed lines in Fig. 2) is adapted from Carter and Easton (1990); the seismic data do not indicate the limit of the CMB west of Lake Ontario. Without further constraints, the seismically imaged boundary zone could include Central Gneiss Belt material.

Beneath Lake Erie, the interpreted seismic image of the boundary zone described below also correlates with a magnetic change from higher values west of the boundary to lower values over the CMB. Here, the less positive magnetic field (Fig. 2), probably indicating Precambrian lithological changes, also coincides with a greater depth to magnetic sources beneath thickened cover rocks. South of eastern Lake Erie, regional linear magnetic anomalies trend south-southwest in general continuity with the interpreted CMB boundary. The anomalies are smoother due to the combined effects of an increasing depth to magnetic sources and a degradation of the 812 m data grid in Lake Erie to a 2 km grid to the south.

From the analogous magnetic anomaly character over four zones of similar geological and seismic reflection attitudes along a strike length of 250 km, we suggest elements of the CMB boundary zone may be traced from exposure to beneath eastern Lake Erie along magnetic anomaly trend. The CMB boundary is characterized by a relatively consistent west to east, positive to negative magnetic anomaly change. The amplitude of the magnetic change varies with lithology and local structure along strike of the boundary, similar to the relationship seen along the exposed boundary. The location of the boundary projected to subcrop from the Lake Ontario seismic images would suggest an eastern limit to the boundary zone analogous to the boundary with Elzevir terrane to the north (White et al. 1994); however, the boundary with the Central Gneiss Belt is not defined west of Lake Ontario. The apparent width of the CMB boundary beneath western Lake Ontario is also similar to the exposed boundary 130 km to the north of Fig. 3*b*. A change of structural attitude indicating the boundary zone cuts across deformation structures in the underlying Central Gneiss Belt (Hanmer and McEachern 1992) is not evident in the Lake Ontario data.

The similar magnetic signature from more positive values over the Central Gneiss Belt to more negative values over the CMB continues at least to the area of eastern Lake Erie. The Bouguer gravity values in the study area range from about -50 to -35 mGal (1 mGal = 10^{-3} cm/s^2) (Forsyth et al. 1992) but are too widely spaced to distinguish the smaller scale changes in upper crustal structure.

The nature of the reflection fabric at mid-crustal levels along the CMB boundary (Fig. 3) changes from a zone of strong, closely spaced, subparallel reflections with apparent easterly dips of 20–25° at the west end of the northern Lake Ontario line to a fabric with more arcuate character and apparent dips of 15–20° beneath southwestern Lake Ontario and Lake Erie. Although the direction of the seismic line changes slightly with respect to the apparent structural (magnetic) strike, we suggest the difference in reflective fabric is more likely due to variations in shear zone geometry with local dip and lithology as noted along the exposed CMB boundary to the north.

A composite cross section of the CMB boundary zone

Correlations between profiles

The reflection fabric at the western ends of the Lake Ontario lines closely matches the dip and depth of principal reflections at the eastern ends of the Lake Erie lines, indicating (*i*) a continuity of deformational style, and (*ii*) a strong possibility that individual upper crustal structures are continuous over the 60 km distance between the ends of the lakes. We have combined three marine profiles (segments 1, 2, and 3 in Fig. 2), which overlap with respect to magnetic anomaly (structural) strike, as a composite 118 km east–west transect of the proposed CMB boundary in the southern study area (Fig. 4). Only the principal structures derived from both final stack and migrated data are interpreted in Fig. 4. Overall data quality is very good. Individual reflections and reflection packages can be traced and correlated with confidence between seismic sections of different vintages and offset along strike. Figure 4 shows similar magnetic anomaly values at the adjacent ends of Lake Ontario and Lake Erie lines and a positive to negative anomaly change similar to that in Fig. 3. From the similarity between seismic dips and exposed CMB boundary attitudes and magnetic anomaly change, we suggest the data from western Lake Ontario data and eastern lake Erie image a zone of similar structural style representing ductile shear elements of the CMB boundary zone. The section extends to about 18 km beneath Lake Erie and more than 20 km beneath Lake Ontario. Antiformal reflections with wavelengths of about 10 km, apparently truncated at their base by east-dipping reflections, are common on both the Lake Ontario sections and on the image of the exposed CMB boundary (White et al. 1994). We interpret the clear reflection geometry at depths of 2.5–5 s (segment 3, Fig. 4) as mylonitic zones bounding thrust slices with easterly dips. The boundaries of the thrust slices have a seismic expression similar to synthetic patterns computed for mylonite zones (Jones and Nur 1984). Using an average velocity of 5.5 km/s (Hobson 1960), upper crustal slices have estimated thicknesses of 1–4 km, similar to interpreted thrust sheet dimensions in the exposed CMB boundary. Possible recurrent thrust sheet patterns are separated by about 10–20 km.

In Lake Erie (segment 1, Fig. 4) the structural style changes significantly with the occurrence of westerly dipping mid-crustal reflections at a major east-dipping zone of reflections interpreted as a thrust zone extending to the lower crust. Similar apparent west-dipping reflections are observed at lower crustal depths beneath the exposed CMB boundary to the north (White et al. 1994). The observed relationship appears to be a plausible representation of the CMB boundary with the Central Gneiss Belt defined "as a zone where the boundary thrust zone cuts across deformation structures in the underlying Central Gneiss Belt" (Hanmer and McEachern 1992, p. 1780).

The interpreted composite model features five geological units, the Central Gneiss Belt, the CMB boundary zone, the CMB, post-Grenville but pre-Paleozoic sedimentary rocks in a basin complex overlying the boundary zone, and the undivided Paleozoic sequence (units $a-e$, Fig. 4). Details of two key elements, the CMB boundary with the Central Gneiss Belt and evidence for extension across the boundary zone, are shown in Figs. 5 and 6.

Central Gneiss Belt

The weakly reflective character of the upper crust within the Central Gneiss Belt contrasts with the stronger reflectivity within the proposed boundary zone and the CMB. The lower reflectivity west of the CMB boundary (Fig. 4) makes it difficult to distinguish multiple reflections or reverberations from Paleozoic strata from possible subhorizontal Precambrian material beneath eastern Lake Erie. Prominent east-dipping reflections observed within the Central Gneiss Belt (lower left, Fig. 4) may indicate shear zones or a subdivision within the Central Gneiss Belt (e.g., the Allochthon Boundary Thrust of Rivers et al. 1989), as has been interpreted west of the exposed CMB boundary to the north (Hanmer 1989) and beneath Lake Huron (Green et al. 1988).

Central Metasedimentary Belt

To the east, we have interpreted an eastern limit to the boundary zone at the top of a zone of strong linear reflections with apparent dips of ~20°. The top of the zone marks the western limit of arcuate and more shallow dipping reflections within the upper crust. Farther east in the CMB, broad arcuate reflections resemble a sequence of repeated hanging-wall anticlines on the leading edges of east-dipping blind thrust sheets that agree with suggested overthrusting to the west (Hanmer and McEachern 1992); however, exposed counterparts to the broad antiforms have not been recognized.

CMB boundary

Figure 5 shows detail I of the interpreted western CMB boundary (Fig. 4). The easterly dipping boundary zone maintains an initial dip of near 30° from beneath Paleozoic cover at about 3 km to a depth of about 10 km where reflections (segment 2 from Lake Erie) become less steep. The interpretation (Fig. 4) suggests a décollement between 12 and 25 km depth. Alternatively steeper dipping events on segment 1 from the line a few kilometres to the north in Lake Erie may indicate boundary structures persist with dips of about 20° to the lower crust. The reflection images suggest the thrust slices are up to about 3 km thick and extend eastward some 50–75 km beneath the CMB. We interpret the 10–30° east-dipping reflections within the boundary zone to originate from a sequence of major thrust sheets similar to those imaged to the north (White et al. 1994). Individual reflections include planar, arcuate, and listric geometries. The variations may indicate that the sheets taper and expand with depth similar to the anastomosing, pinch and swell form in plan of high-strain zones mapped within the boundary zone to the north. The seismic data will not image possible steeply dipping structures near fold axes.

In summary, within the proposed extension of the western CMB boundary zone, upper crustal dipping reflections (detachment surfaces?) are remarkably uniform in dip to at least 25 km and perhaps deeper beneath western Lake Ontario. Some structures may sole into gently east-dipping detachments beyond the depth of the seismic data. Interpreted thrust sheets that bound broad antiformal structures are spaced at intervals of from 5 to 15 km. The interpreted CMB boundary features an easterly dipping reflective zone that appears to truncate underlying reflections with apparent west dips at middle to lower crustal depth. Within the lower crust, Central Gneiss Belt rocks may extend 50–75 km to the east, covered by more than 20 km of CMB thrust sheets. The possibility that the upper crust beneath western Lake Ontario is a southward extension of the Elzevir terrane is discussed in Forsyth et al. (1994). The reflections interpreted as the CMB boundary resemble images from the Grenville Front beneath Lake Huron (Green et al. 1988).

Reactivation of basement structures

Figure 6 shows detail II from Fig. 4. A marker horizon for shallow seismic interpretation is the top of the Middle Ordovician Trenton Group, represented by a shale–limestone contact. The gently west-dipping reflections at a depth of 2.5 km indicate an angular unconformity with the overlying Paleozoic section. Small undulations within the reflective zone coincide with steeper, apparently west-dipping reflections from the Grenville basement. Figure 4 indicates the reflective zone with gentle apparent west dip extends from beneath the eastern shore area of Lake Erie at less than 0.5 km depth to 3–4 km depth over the CMB boundary zone and appears truncated to the west by east-dipping reflections that continue to depth within the boundary zone. The reflective zone with gentle apparent west dip is evident on both lines from Lake Erie and is interpreted to represent a local basin of post-Grenville sediments. Alternatively, the basin may represent rotated strata in the hanging wall of a pre-Paleozoic growth fault. The highly reflec-

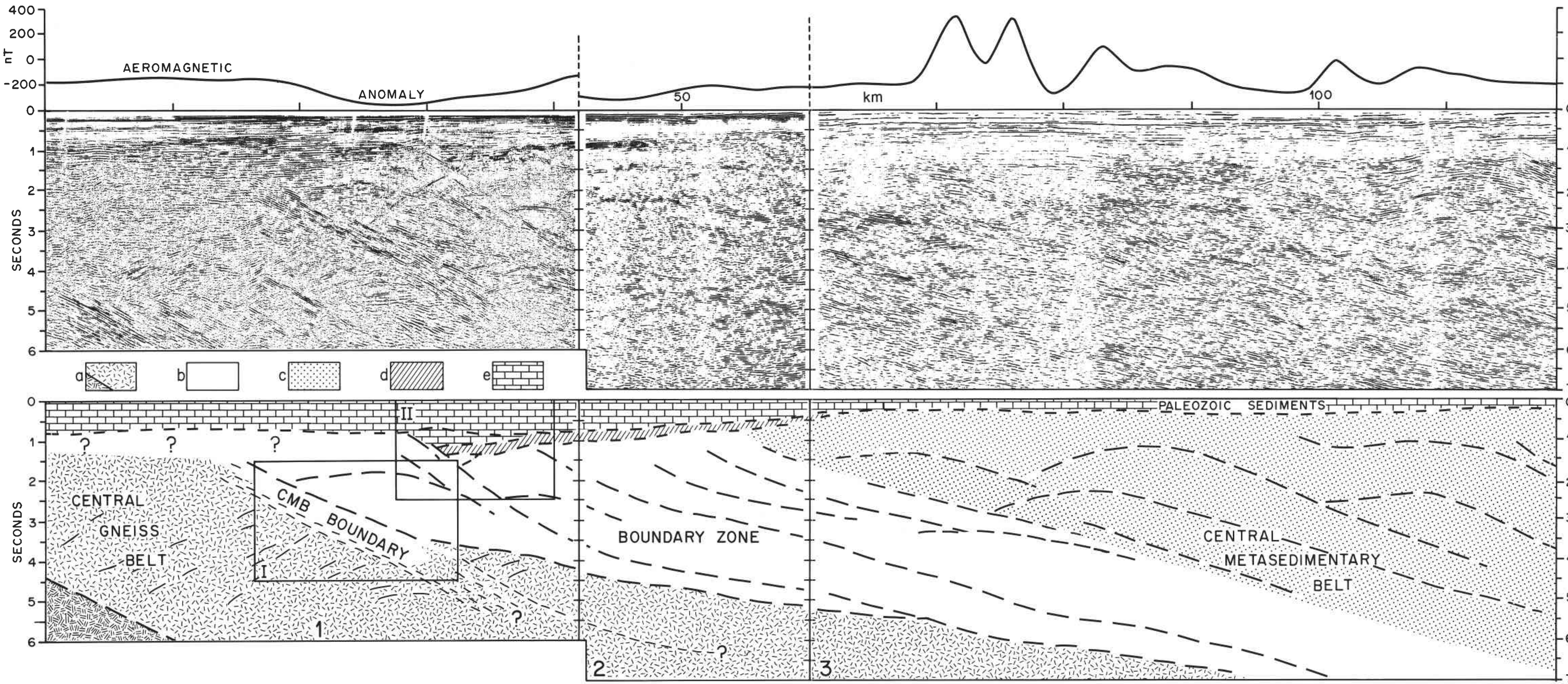

Fig. 4. East–west composite data section (top) and interpretation (bottom) across the CMB boundary zone. Interpretation is based on migrated sections and adjacent seismic profiles. An average velocity of 6 km/s was used for depth estimates. Note positive to negative magnetic change across the CMB boundary similar to profiles in Fig. 3. *d*, post-Grenville sediments; *e*, Paleozoic strata. Details of boxes I and II are shown in Figs. 5 and 6.

tive and multicyclic nature of the reflection sequence resembles reflections from the lower portion of shelf strata overlying Grenville basement beneath the northern (Spencer et al. 1989) and southern Appalachians (Hubbard et al. 1991). The relationship to basement features suggests a basin controlled by reactivated structures within the CMB boundary zone.

We interpret Fig. 6 as indicating extension during and (or) following deposition of post-Grenville (shelf?) sediments. The extension, apparently east–west, appears to have occurred along planes similar to the original thrusting in the Grenville basement and may have been accommodated on growth faults (Wagner 1976). Examples of similar structures are basins in western Ohio (Shrake et al. 1991) and the Rome Trough in Kentucky and West Virginia (e.g., Braile et al. 1982).

In contrast with observations by Hubbard et al. (1991), a late phase of Grenville basement extension may have followed deposition of the shelf strata in the study area. The Trenton Group (Middle Ordovician limestone strata) provides uniform cover of the study area. Using isopach maps (Bailey Geological Services Ltd. and Cochrane 1984; Rickard 1973) and average velocities between 5.5 and 6.0 km/s (Hobson 1960; Ontario Hydro 1979), regional values of reflection times to the top of the Trenton Group and Precambrian basement were estimated. Forward modelling of sonic logs from a well north of the seismic transect (T in Fig. 6) confirms the Trenton as a marker horizon. Reflections from this level within the Paleozoic section have not been subsequently offset. Depths to the Trenton estimated from isopach maps (about 350 m below sea level in southern Lake Erie, and about 100 m below sea level in eastern Lake Ontario) agree well with the reflection times for the length of the composite profile.

Assuming an approximately uniform cover of Precambrian sediment, extension-produced uplift of the Central Gneiss Belt relative to the CMB and consequent thinning–erosion may have removed most of the post-Grenville sedimentary rocks west of the reactivated CMB boundary. Using the post-Grenville sediments as an indicator, it appears that the basement between the CMB boundary and the post-Grenville sequence remained fixed to the Central Gneiss Belt and was not significantly reactivated during later extension; the differential movement appears best documented on structures within the boundary zone (Fig. 4).

Renewed compression may have occurred in Cambro-Ordovician time: the gently arched reflections in the upper paleobasin (U in Fig. 6) may be due to compressional or transpressional reactivation of basement structures. We speculate this may have been associated with strike-slip (wrench) faulting, indicating a change of the regional stress field (Beardsley and Cable 1983) in the early Paleozoic. The origin of the U reflection is not clear but may be correlative with an early Paleozoic unconformity (for example, Lower Ordovician Knox dolomite, indicating the extent of shelf carbonates). Although limited borehole data from the lower Paleozoic strata to Precambrian unconformity described below suggest local topography on the unconformity near the proposed boundary zone, since deposition of the Middle Ordovician Trenton Group (T in Fig. 6), no major or cumulative offsets of marker horizons by growth faulting from reactivated Grenville structures are observed in these data.

Borehole data between lakes Ontario and Erie

South of lakes Ontario and Erie the eastern Appalachian Basin is one of the better documented Paleozoic sedimentary basins (Bailey Geological Services Ltd. and Cochrane 1984; Rickard 1973); however, there are few data from boreholes penetrating Precambrian basement in the study area and even less data from cores (Fig 4). Clearly, an understanding of the interaction between basement structures and overlying sediments is basic to understanding Late Proterozoic and early Paleozoic evolution in the area. Sandford et al. (1985) have suggested that rejuvenated Precambrian basement elements have influenced hydrocarbon accumulation in the Paleozoic section. A detailed seismic interpretation is hampered by the lack of coincident boreholes and the uncertain Precambrian surface in nearby wells (Bailey Geological Services Ltd. and Cochrane 1984, p. 24).

Isopach data (Sanford 1961) for the Ordovician Trenton Group and Black River Group strata change from relatively uniform thicknesses west of the CMB boundary to a complex system of valleys and ridges coinciding with the general trend and extension of the CMB boundary in Fig. 4. The variable thickness of basal Cambrian clastics also indicates significant local relief along the Precambrian unconformity. For example, the Cambrian section thickness is a few tens of metres from wells near western Lake Ontario and south of Lake Erie in contrast with over 100 m (Fig. 7) from wells along the north shore and beneath eastern Lake Erie. Borehole rock chip samples suggest the Precambrian basement was deeply weathered (depths ≈ 10 m from well completion reports, Fig. 7) prior to deposition of shelf strata. The well log from Erie County, New York, about 17 km east of the Lake Erie seismic line,

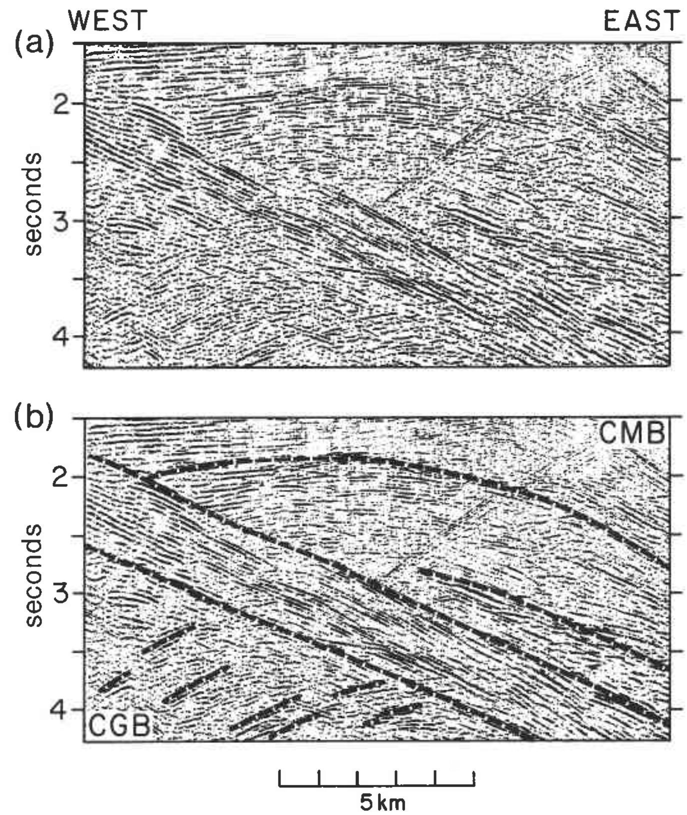

FIG. 5. 1985 Lake Erie air-gun data (*a*) and interpretation (*b*) from CMB boundary zone (box I, Fig. 4). The linear, multicyclic reflections dipping eastwards at 30°E from approx. 1.75 s (two-way time) are interpreted as a mylonitic thrust zone separating the Central Gneiss Belt footwall from the CMB boundary zone hanging wall. The higher frequency, westerly dipping reflection (upper right) is from steep westerly dipping structure in Fig. 6.

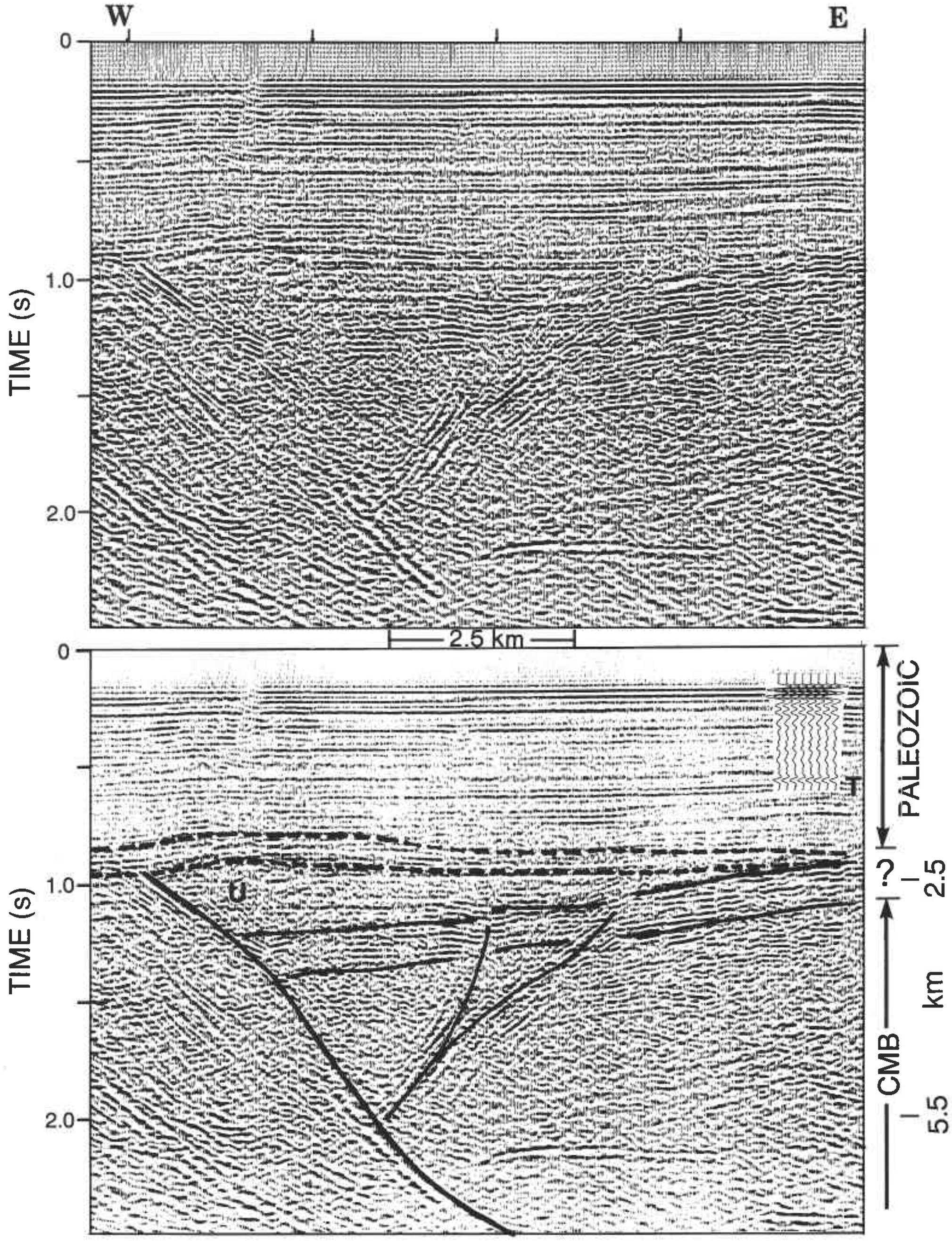

FIG. 6. Migrated reflection data (top) and interpretation (bottom) from within the CMB boundary zone (box II, Fig. 4). Extension along presumed Proterozoic structures has influenced paleobasin formation. Trenton strata (T), interpreted using synthetic seismograms, is at about 0.55 s and top of Precambrian basement at about 0.8 ms. U, gently arched reflections described in text.

indicates 22 m of "arkose" and "granite wash" (Fig. 7). Locally "granite wash" (coarse-grained quartz granules and pebbles, Bailey Geological Services Ltd. and Cochrane 1984) has been preserved beneath Cambrian strata on the Precambrian surface. Borehole data do not show whether this apparently reworked Precambrian material is part of the Cambrian strata or a Precambrian deposit. Published isopach maps of the lowermost Paleozoic (Bailey Geological Services Ltd. and Cochrane 1984) do not distinguish between weathered gneissic–granitic basement rocks or arkose and Paleozoic strata. North of Lake Ontario, pre-Paleozoic, post-Grenville sediment is described by Wilson and Dugas (1961) and Easton et al. (1990). We suggest our data indicate basement structural influence in the development of half grabens that have preserved Late Cambrian and (or) pre-Paleozoic material related to material sampled from holes near eastern Lake Erie. To the southwest, Shrake et al. (1991) have reported similar basins of Precambrian clastic material beneath Ohio.

Borehole data are also insufficient to map Precambrian surface topography or local basins of pre-Paleozoic material diagnostic of the CMB boundary. Clues to tectonic events between amalgamation of the Grenville Province at about 1.06 Ga and deposition of Cambrian sediments at about 0.55 Ga are in the geological relationships near the unconformity. Cored sections through the Precambrian unconformity under eastern Lake Erie would be very valuable.

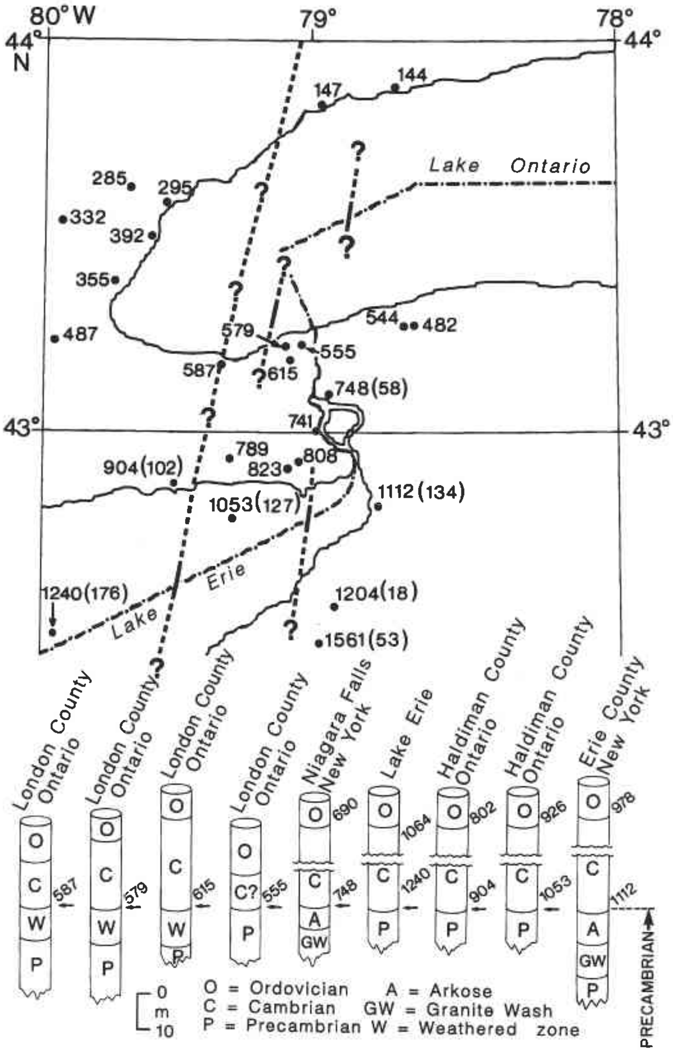

FIG. 7. Data from holes penetrating nominal Precambrian material along the CMB boundary zone (dashed line). Borehole sections coded by elevations below sea level at top Cambrian and Precambrian. Sections are shown levelled at Precambrian unconformity (arrows). Numbers in parentheses are thicknesses of basal Cambrian sandstone. Note depth scale, thicker Cambrian section near eastern Lake Erie, and variation in possible Precambrian clastic material. Sources: well completion reports, Petroleum Resources Laboratory, Ministry of Natural Resources, London, Ontario; Kreidler 1963; Kreidler et al. 1972; Waller et al. 1978; Van Tyne 1975; American Industrial Disposal Systems 1968*a*, 1968*b*.

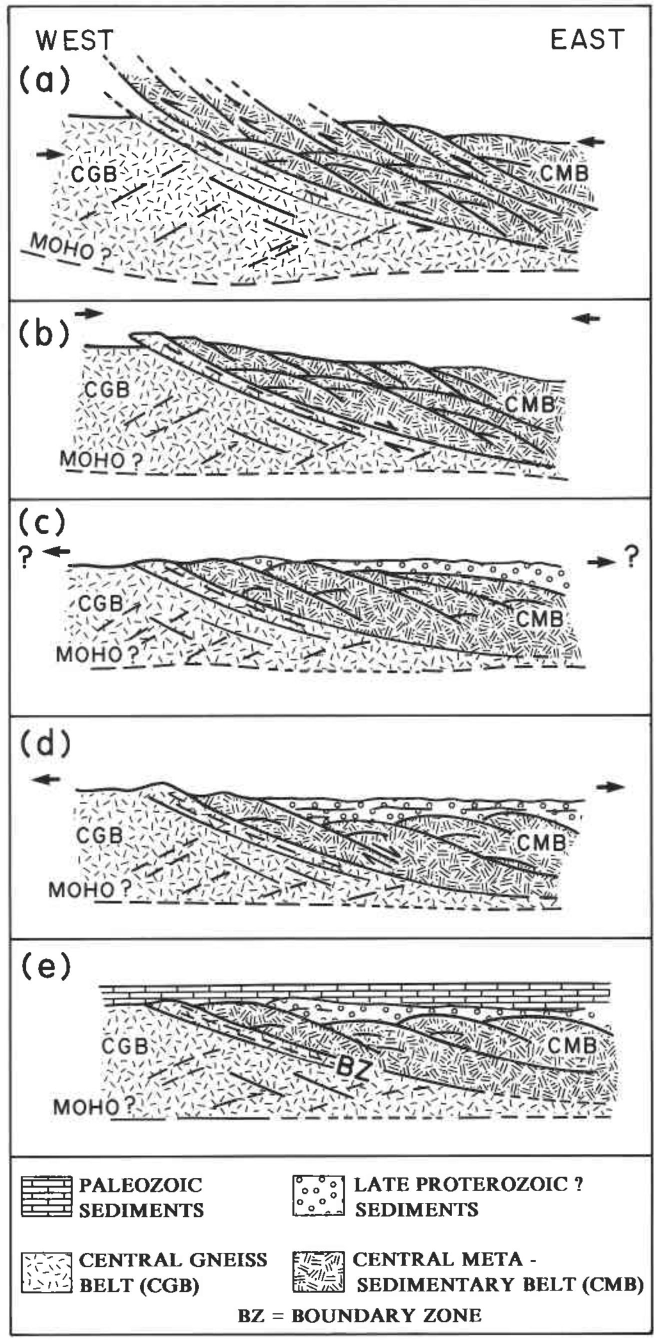

FIG. 8. Schematic east–west sections illustrating the tectonic development of the CMB boundary from the Mid-Proterozoic to Paleozoic. (*a*) Creation of a thickened crust near the CMB boundary. (*b*) Synorogenic collapse of the lower crust. (*c*) Exhumation to middle to lower crustal depth; local basin development. (*d*) Subsidence, deposition of Late Proterozoic – early Paleozoic clastics, disruption of the Grenville platform due to (failed?) rifting. (*e*) Local extensional reactivation of existing structures and (1) deposition of Cambrian? sediments mainly east of CMB boundary and (2) relatively undisturbed deposition of Paleozoic sediments.

Tectonic model

The imaged crustal geometry is consistent with a tectonic model that includes westerly accretion of crustal slices during the Grenville orogeny, uplift and erosion, sedimentation, extension and formation of post-Grenville paleobasins, possible minor renewed uplift of the Central Gneiss Belt relative to the CMB, and subsequent deposition of Paleozoic strata. Surface mapping (Hanmer 1988) and seismic images indicate that the CMB boundary has moderate easterly dips of 20–30°. Seismic and geological data suggest the CMB has been thrust over the Central Gneiss Belt along east-dipping zones that extend to the lower crust.

Our tectonic cartoon for development of the CMB boundary zone from Middle Proterozoic to Paleozoic (Fig. 8) starts with convergence between the CMB and Central Gneiss Belt at about 1.2 Ga (Hanmer and McEachern 1992). This situation may have resulted from collision and subduction (Windley 1986) followed by compression of an island-arc – back-arc basin complex represented by marginal-basin tholeiitic suites of volcanics in Elzevir terrane (Smith and Holm 1990). The general easterly dipping crustal architecture evident in the CMB boundary zone seismic images probably developed at middle to lower crustal depths during episodes of Grenville thrusting between about 1.2 and 1.05 Ga, perhaps locally incorporating Central Gneiss Belt material from the footwall and creating an overthickened crust (Mezger et al. 1991) (Fig. 8*a*). The CMB boundary zone is interpreted as developing into a series of moderately dipping ductile thrusts at middle to lower crustal levels (Fig. 8); however, more steeply dipping crustal faults, which may have developed during extension, cannot be ruled out (Fig. 4). The structural fabric may have been rejuvenated in synorogenic collapse or posttectonic extension between 1.04 and 0.94 Ga (Fig. 8*b*).

Clear seismic constraints have not yet been recognized to resolve tectonic events during exhumation of the Grenville basement (Fig. 8*c*) such as disruption of the post-Grenville platform due to (failed?) rifting prior or during deposition of Late Proterozoic – earliest Paleozoic shelf strata. The regional extent of pre-Paleozoic sediment cover is also uncertain. Subsidence, involving rejuvenated Grenville structures in conjunction with deposition of Early Cambrian sediments east of the CMB boundary, would produce a system of half grabens (Fig. 8*d*). This may have been followed by minor renewed compression along the CMB boundary and erosion west of the CMB boundary. Finally, deposition of Paleozoic sediments after 0.55 Ga formed the Appalachian Basin (Fig. 8*e*). Higher resolution data from the Precambrian unconformity to the surface are required to constrain later (post-Taconic) events. The discovery of kilometre-thick basins of probable Late Proterozoic clastic sediments by Shrake et al. (1991) and this study indicate that much important Late Proterozoic – early Paleozoic tectonic information may yet be derived from studying the relationship between clastic sediments and the structure of the immediately underlying Grenville basement.

Implications

The relationship between Grenville basement structures and the late Precambrian to Early Cambrian sedimentary units and possibly the better explored Paleozoic units have implications for the following:

(1) Regional hydrogeological conditions and models for deep-well waste disposal—Many disposal wells discharge material near the Precambrian–Paleozoic unconformity.

(2) Deep exploration for hydrocarbons—A number of structures occur in the subsurface beneath the well-explored Cambrian–Ordovician section. Exploration wells have shown the existence of post-Grenville sedimentary units (granite wash, buff dolomites, arkose) left in faulted basement blocks and some have hydrocarbon shows (Bailey Geological Services Ltd. and Cochrane 1984).

(3) Earthquake hazards—From western Lake Ontario, the structures apparently related to the CMB boundary zone extend through the depth range of low-level seismicity to the east beneath the CMB. Southeast of the study area, earthquakes have been associated with faulting in the Grenville basement; it has been speculated that these faults have been intermittently active from the Precambrian to the present (Pohn and Coleman 1991).

Conclusions

(1) Successful extended correlation and reprocessing of industry marine seismic data has distinguished crustal reflection geometry to lower crustal depths in the central Grenville Orogen. The reflectivity of deep structure beneath lakes Ontario and Erie indicates that seismic reflection can successfully improve our understanding of the crustal structure; a shallow, higher resolution survey is required to resolve structural relationships near the Precambrian–Paleozoic unconformity.

(2) Potential field data, calibrated both by mapped and seismic structures, are used to link Paleozoic-covered Grenville structures with exposed geology to the north; available borehole data help constrain the interpretation. From the consistent nature of the magnetic anomalies and their relationship to seismic and mapped structure, we suggest the CMB boundary extends some 200 km to eastern Lake Erie.

(3) Seismic images of apparent thrust sheets 1–5 km thick with easterly dips and apparent truncations resemble geological models of the CMB boundary to the north. Seismic data clearly image internal structures within the western CMB and provide geometric constraints on the relationship between terranes within the CMB. The relationship of the magnetic anomalies to mapped lithologies suggests that upper crustal Central Gneiss Belt rocks in the footwall of the CMB boundary are of generally higher magnetic susceptibility than nearby rocks to the east.

(4) Beneath eastern Lake Erie and western Lake Ontario, marine reflection images reveal clear patterns of an easterly dipping (10–30°) reflective fabric that is interpreted to include planar, arcuate, and listric geometries for the middle to upper crust of the CMB boundary. Apparent thrusts may sole into gently east-dipping detachments beyond the depth of the seismic data. Antiformal and linear reflective zones are interpreted as highly deformed gneiss and mylonite. The crustal structure of the western CMB has the form of broad hanging-wall anticlines on the edges of blind thrusts.

(5) Extension along the CMB boundary zone is indicated by (*i*) preserved post-Grenville sediments in half-graben basins controlled by apparent normal fault adjustment along basement (thrust?) structures (Fig. 6), (*ii*) relative uplift of the Central Gneiss Belt with respect to the CMB (van der Pluijm and Carlson 1989), and (*iii*) thicker Cambrian section at the eastern end of Lake Erie as indicated by well data (Fig. 7). Structures that have influenced the basins appear to extend to mid-crustal depth.

(6) The seismic images of truncated arcuate, fold-like structures and dipping reflections that continue to the lower crust are similar to images from areas in the northern Appalachians (Ando et al. 1984) and in older areas, such as the Great Lakes Tectonic Zone in Minnesota (Smithson and Johnson 1989). Apparent dips of upper crustal reflections from the CMB boundary zone resemble exposed attitudes in the boundary to the north. The similarity between our seismic data and data near the Grenville Front (Green et al. 1988) suggests that strongly reflective, crustal-scale zones of ductile deformation may be common within the Grenville Orogen. Analogous features of these data are dipping, multicyclic reflections believed to be generated by mylonite zones along thrusts that can be traced with dips of approximately 15–30° to depths of at least 25 km. The seismic images presented here appear to support geological interpretations (Davidson 1986) of lateral growth of continental crust during the Grenville orogeny by northwest accretion of CMB terranes thrust over the older rocks of the Central Gneiss Belt.

(7) This study provides an initial framework to study the relationship between structures and seismicity in the study area. We have provided evidence for east-dipping structure within the range of hypocentre depths beneath lakes Ontario and Erie

(Basham and Cajka 1985). Better defined hypocentres, nodal plane solutions, and constraints on the nature of the local stress field are required to clarify the relationship between earthquakes and structures. Within the resolution of our data, there is no evidence for major or cumulative movement and (or) significant tectonic rejuvenation in the area since deposition of the Trenton strata.

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