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THE BEDROCK SURFACE OF THE WESTERN LAKE ONTARIO REGION: EVIDENCE OF REACTIVATED BASEMENT STRUCTURES?

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ABSTRACT Lower Paleozoic bedrock strata, in south-central Ontario and the adjacent part of New York State are covered by a thick (100m+) blanket of Pleistocene glacial and interglacial sediments. The form of the buried bedrock surface has been reconstructed from 70,000 waterwell boreholes that extend through the entire Pleistocene cover using GIS data processing techniques. The sub-drift bedrock surface shows linear channels that connect the basins of lakes Huron, Ontario and Erie and which form part of an ancestral mid-continent Great Lake drainage system prior to modification and infilling during successive Pleistocene glaciations. This relict drainage system is cut across Lower Paleozoic carbonates and clastics up to 500 m thick, but the position of several channels is aligned above terrane boundaries, faults and other deep-seated and poorly understood geophysical anomalies in underlying mid-Proterozoic Grenville basement rocks. Other channels are controlled by a dominant northwest and northeast trending regional joint system. A close relationship among deeply seated geophysical lineaments, basement structures and topographic lineaments cut across thick Paleozoic cover strata suggests a history of Phanerozoic reactivation and upward propagation of fractures from the Precambrian basement. Several basement structures and lineaments are seismically active suggesting ongoing neotectonic activity across the 'stable' craton of south-central Ontario.

RÉSUMÉ *La surface de la roche de fond dans la partie ouest du lac Ontario: indices de réactivation des structures du socle.* Les couches géologiques de la roche de fond du Paléozoïque inférieur, dans le centre sud de l'Ontario et la partie adjacente de l'État de New York, sont recouvertes par une grande épaisseur (> 100 m) de sédiments glaciaires et interglaciaires. La forme de la surface de la roche de fond enfouie a été reconstituée à partir de 70 000 puits de sondage qui traversent toute la couverture du Pléistocène. La surface sous les dépôts glaciaires laisse voir des chenaux linéaires qui relient les bassins des lac Hurons, Ontario et Érié et qui forment une partie de l'ancien système de drainage des Grands Lacs. Ce réseau de drainage relique entaille les carbonates du Paléozoïque inférieur et les dépôts détritiques jusqu'à 500 m d'épaisseur, mais l'emplacement de plusieurs chenaux est aligné au-dessus des limites de la formation fissurée, des failles et autres anomalies géophysiques profondes et mal connues du socle grenvillien du Protérozoïque moyen. D'autres chenaux sont sous la dépendance d'un réseau de fractures en grande partie orientées vers le NW et vers le NE. Les fortes relations qui existent entre les linéaments géophysiques profonds, les structures du socle et les linéaments topographiques entaillant l'épaisse couverture paléozoïque laissent entrevoir une réactivation au Phanérozoïque et une propagation ascendante des fractures à partir du socle précambrien. Plusieurs structures et linéaments du socle sont sismiquement actifs signalant ainsi une activité néotectonique continue à travers tout le craton dit stable du centre-sud de l'Ontario.

ZUSAMMENFASSUNG *Die Sockeloberfläche im Gebiet des westlichen Ontariosees: Beweis für reaktivierte Grundstrukturen?* Die Sockelstrata aus dem unteren Paläozoikum im südlichen Zentrum von Ontario und dem angrenzenden Teil des Staates New York sind von einer dicken (100 m+) Decke glazialer und interglazialer Pleistozänsedimente überlagert. Die Form der vergrabenen Oberfläche des Sockels ist mittles 70 000 Brunnenbohrlöchern, die durch die ganze Pleistozändecke hindurchgehen, rekonstruiert worden. Die Sockelobergläche unter den glazialen Ablagerungen zeigt lineare Rinnen, welche die Becken des Huron-, Ontario-und Eriesees miteinander verbinden und Teil eines alten halbkontinentalen Drainagesystems der Großen Seen bilden. Dieses Reliktdrainagesystem schneidet quer durch die Karbonate des unteren Paläozoikums und die Trümmergesteine bis zu einer Dicke von 500 m, aber die Position gewisser Rinnen ist oberhalb der Grenzen der gespaltenen Foramation, den Verwerfungen und anderen tiefgelegenen und schlecht verstandenen geophysikalischen Anomalien der darunterliegenden Felsen des Grenville-Unterbaus aus dem mittleren Paläozoikum ausgerichtet. Andere Rinnen werden durch ein regionales Kluftsystem, das vor allem nach Nordwesten und Nordosten ausgerichtet ist, kontrolliert. Eine enge Beziehung zwischen tief gelegenen geophysikalischen Lineamenten, Unterbaustrukturen und topographischen Lineamenten, deuten auf eine Reaktivierung im Phanärozoikum und eine aufsteigende Verbreitung der Brüche vom Unterbau des Präkambriums. Mehrere Unterbaustrukturen und Lineamente sind seismisch aktiv und zeigen so eine anhaltende neotektonische Aktivität quer durch den als "Stabil" angesehenen Kraton vom südlichen Zentrum Ontarios.

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INTRODUCTION

There is considerable discussion of the potential for damaging intraplate earthquakes in the heavily urbanised south-central Ontario region and the adjacent area of New York State (Mohajer, 1993), there being a greater risk of a major earthquake (M ≈ 7) than hitherto believed (Adams *et al.*, 1993). This concern has focussed attention on the geologic record of neotectonic activity in the region (*e.g.* Mohajer *et al.*, 1992). Current research is focussed on prominent, but poorly understood, geophysical lineaments and tectonic structures identified in middle Proterozoic basement below thick Paleozoic and Pleistocene cover strata. Reactivation of deeply-seated structures during the Phanerozoic is suggested by a spatial correlation with historic and instrumented earthquake epicentres around the western end of Lake Ontario (Mohajer, 1991). The most well known seismically-active structure lies just east of the present study area and extends from western New York State across Lake Ontario into Ontario as the Clarendon-Linden fault (Isachsen and McKendree, 1977; Hutchinson *et al.*, 1979). Other seismically active structures underlie the western end of Lake Ontario between Hamilton and Toronto where there is a well-defined cluster of recent earthquake epicentres (Mohajer, 1993). Ongoing work on bedrock buckles (pop-ups; Wallach *et al.*, 1993) and on regional joint sets (Scheidegger, 1977, 1980; Daniels, 1990; Engelder, 1982; Rogojina, 1993) emphasises the presence of high horizontal compressive stresses in the continental interior of eastern North America (*e.g.* Zoback, 1992).

In the Lake Erie basin of southwestern Ontario, Sanford *et al.* (1985) identified the effect of episodic Phanerozoic reactivation of Proterozoic basement structures on the development of oil reservoirs in Paleozoic strata. This work was facilitated by access to a wealth of subsurface oil well data. Unfortunately, an equivalent data base does not exist for the western Lake Ontario region where there is no preserved sedimentary record between the Silurian and the Pleistocene. The objective of this paper is to show that the sub-Pleistocene bedrock surface in the western Lake Ontario region provides important information regarding the Phanerozoic tectonic history of the area by demonstrating a geographical association among bedrock surface lineaments, basement structures and geophysical anomalies. These data are most easily interpreted as evidence of upward fracture propagation from deeply-buried Proterozoic structures.

THE STUDY AREA

The area of investigation extends over some 3400 km^2 from the Niagara Escarpment in the west, eastward to Rice Lake and from Georgian Bay in the north to the Niagara Peninsula in the south (Figs. 1 and 2). This region includes the Greater Toronto Area and contiguous urban communities located at the western end of Lake Ontario. The study area is underlain by southwesterly-dipping Ordovician and Silurian cover strata up to 500 m thick (Fig. 2) (Johnson *et al.*, 1992). The region has been subjected to repeated glaciations, but preserved sediments, up to 200 m thick, appear to be no older than about 100,000 years (Karrow, 1984; Eyles and Williams, 1992; Berger and Eyles, 1994). A large portion of Phanerozoic time has gone unrecorded as a result of episodic uplift along the northern margin of the Appalachian Basin. The limit of Paleozoic cover strata lies north of the study area where mid-Proterozoic basement outcrops across the exposed Canadian Shield (Figs. 1 and 2).

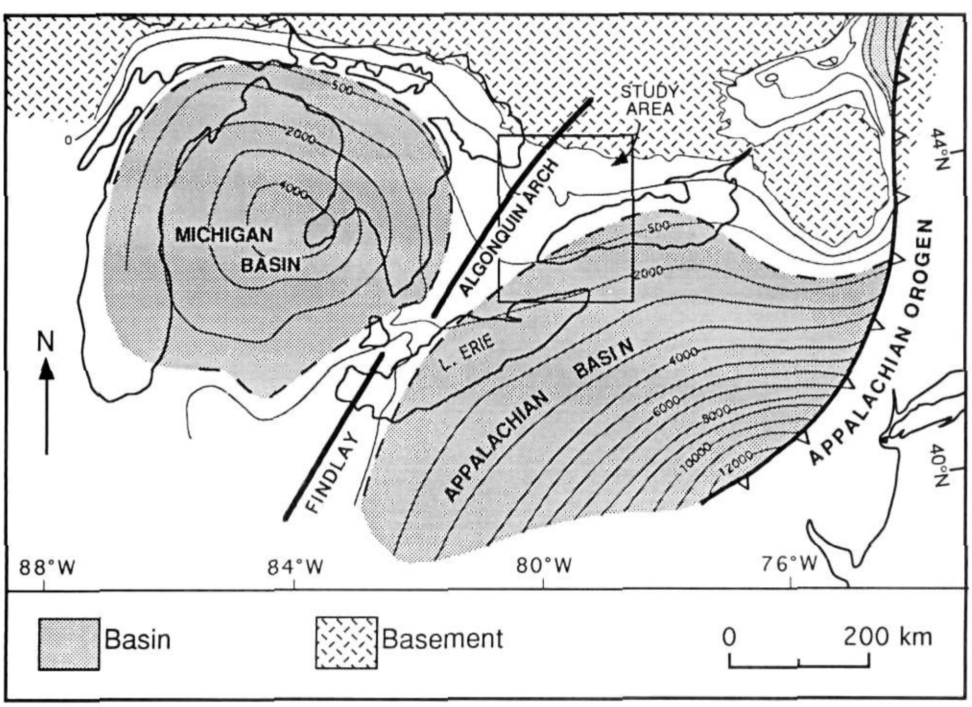

FIGURE 1. Basinal setting of southern Ontario with the western Lake Ontario region shown as inset (after Sanford *et al.*, 1985 and Johnson *et al.*, 1992). Repeated Phanerozoic thrusting along the eastern continental margin of North America has resulted in episodic forebulging of the Findlay-Algonguin arch (see text) (contours in metres).

Configuration des bassins du sud de l'Ontario (selon Sanford et al.*, 1985 et Johnson* et al.*, 1992). La région à l'étude est encadrée. Le charriage répété le long de la marge continentale orientale de l'Amérique du Nord a causé le soulèvement épisodique de l'arc Findlay-Algonquin (voir le texte) (courbes en mètres).*

GEOLOGICAL AND STRUCTURAL FRAMEWORK

This section provides a brief overview of the bedrock geology and structure of the western Lake Ontario region as a background to a detailed examination of bedrock topography. The term 'craton' or shield is commonly used to refer to low-relief areas of exposed basement juxtaposed with areas covered by flat-lying, platformal sedimentary strata (see Leighton, 1990). The western Lake Ontario region lies in a central position on the North American craton close to the transition from shield to platform (Figs. 1-3) and, thus, is particularly appropriate for examining structural relationships between basement and overlying cover strata.

BASEMENT

Basement below the western Lake Ontario region comprises several discrete terranes of mid-Proterozoic age lying within the Grenville Province of the Canadian Shield (Davidson, 1986; Hoffman, 1989; Easton, 1992; Fig. 3). The Grenville Province can be subdivided into the Central Gneiss Belt (CGB), composed of quartzofeldspathic gneiss and amphibolite facies dated at >1.35 Ga, and the Central Metasedimentary Belt (CMB) that is composed of supracrustal strata invaded by plutonic rocks about 1.1 Ga in age (Easton, 1992). The boundary between the CGB and CMB is the Central Metasedimentary Belt Boundary Zone (CMBBZ; Fig. 3) which is demarcated by the prominent Niagara-Pickering magnetic lineament (Wallach, 1990). The CMBBZ is a major tectonic boundary and is known to extend through the entire crust (Easton, 1992). Milkereit *et al.* (1992) identified easterly-dipping thrust faults below the CMBBZ recording suturing of a mid-Proterozoic continental margin. Thrusts dip eastward at about 30°, passing below the western end of Lake Ontario. A band of closely-spaced aeromagnetic lineaments between Lake Erie, in the south, and the surface exposure of the CMBBZ in the north define a broad zone as much as 30 km wide (Gupta, 1991b). The CMBBZ is seismically

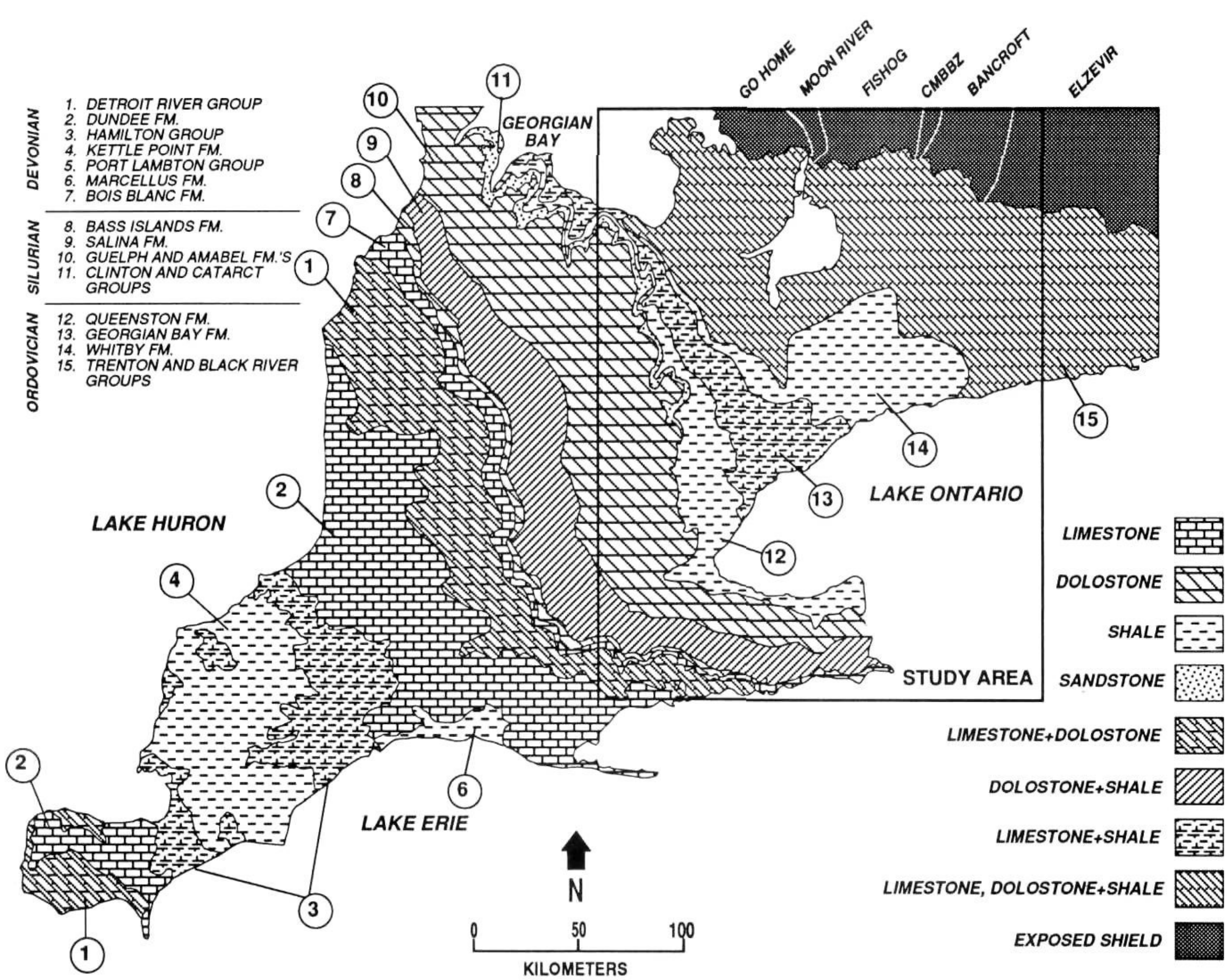

FIGURE 2. Paleozoic geology of southern Ontario (after Ontario Geological Survey, 1991, 1992; Liberty, 1969; Johnson *et al.*, 1992). Geology of covered and exposed shield is shown in Figures 3 and 6. Study area is shown by box.

Géologie paléozoïque du sud de l'Ontario (selon la Commission géologique de l'Ontario, 1991, 1992; Liberty, 1969; Johnson et al., *1992). La géologie du socle à nu et enfoui est illustrée aux figures 3 et 6. La région à l'étude est encadrée.*

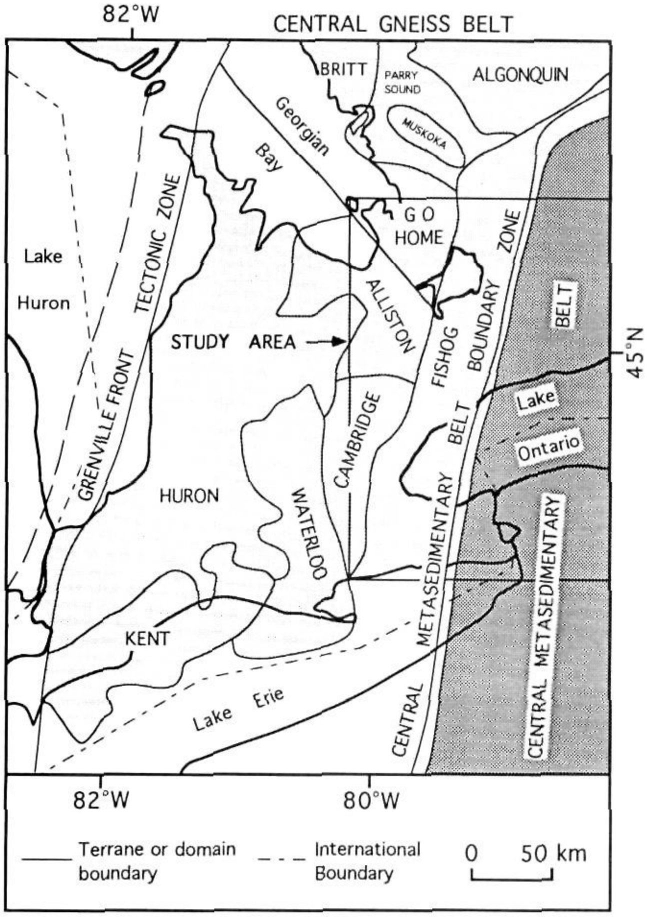

FIGURE 3. Middle Proterozoic terranes in the Grenville Province of southern Ontario (after Hoffman, 1989; Easton, 1992). Inset shows study area. The extension of terranes under the Paleozoic cover strata is tentative; reconstruction of the surface topography of Paleozoic strata buried below Pleistocene glacial sediments can be used to further constrain the position of terrane boundaries (see Figs. 6, 7).

Divisions du Protérozoïque moyen de la Province de Grenville, au sud de l'Ontario (selon Hoffman, 1989 et Easton, 1992). La région à l'étude est encadrée. Le prolongement des divisions sous la couverture paléozoïque est provisoire. La reconstitution de la topographie de surface de la couche paléozoïque enfouie sous les sédiments glaciaires pléistocènes peut servir à mieux cerner l'emplacement des limites des divisions (voir fig. 6 et 7).

active in Ohio and Québec but is presently inactive below Lake Ontario (Mohajer, 1993).

The study area straddles several discrete lithotectonic domains within the CMB and CGB. These are mapped by reference to differences in metamorphic grade and structure and record the successive accretion of displaced terranes to the southeast margin of Laurentia during the Grenvillian Orogeny after 1200 Ma. Figure 3 shows the approximate position of the terranes based on about 600 widely-spaced drill holes that penetrate the Paleozoic cover (Easton, 1992). The boundaries of these terranes are not precisely located, but take the form of narrow, structural breaks and thrust faults that are intensely sheared (*e.g.* Davidson, 1986; Culotta *et al.*, 1990). On the exposed Grenville to the north there are contrasts in crustal thickness, metamorphic grade on either side of these structures and brittle faults which are not consistent with a deep crustal origin and which suggest episodic reactivation during the Phanerozoic (Easton, 1992). Several structures have a prominent aeromagnetic expression through thick and low magnetic susceptiblity Paleozoic and Pleistocene cover strata. It is not yet possible to separate inactive, healed structures from those that may be active; all boundary zones in south-central Ontario must therefore be considered potentially active.

PALEOZOIC COVER

Southern Ontario lies along the eastern rim of the Michigan Basin which is demarcated by a Proterozoic structural high (Findlay-Algonquin Arch; Fig. 1). This forms a distinct northeast-trending 'spine' overlain by a relatively thin cover of Paleozoic strata (1525 m max; Johnson *et al.*, 1992) separating the much thicker Paleozoic infills of the Michigan Basin (4800 m; Catacosinos and Daniel, 1990) and the Appalachian Basin (13,000 m) (Fig. 1).

The distribution of Lower Paleozoic strata in the western Lake Ontario region is shown in Figure 2; the northern margin of Paleozoic cover rocks runs approximately west-east across the northern boundary of the study area. The distribution, stratigraphy and age of such rocks has been reviewed in detail by Johnson *et al.* (1992). Ordovician strata are exposed east of the Niagara Escarpment and Silurian and younger rocks comprise the escarpment and areas further west of the study area; Paleozoic strata are about 500 m thick at the western end of Lake Ontario. Johnson *et al.* (1992) recognised several unconformity-bounded depositional sequences within the Paleozoic cover strata that resulted from alternating subsidence and uplift of the Findlay-Algonquin Arch. Movement of the arch occurs as a 'forebulge' that responded to changing structural loads along the eastern continental margin of North America during successive orogenic cycles (*e.g.* Quinlan and Beaumont, 1984; Sanford *et al.*, 1985; Sanford and Smith, 1987; see below).

DATA BASE FOR REGIONAL BEDROCK TOPOGRAPHIC RECONSTRUCTION

There have been several previous attempts to identify the form of the buried bedrock surface around the margins of Lake Ontario. Spencer (1881) investigated the Tertiary and Quaternary drainage history of the Great Lakes basin and identified a prominent bedrock low connecting the deeper bedrock basins of Georgian Bay and Lake Ontario. This depression (Laurentian Channel; see below) is filled with Pleistocene glacial sediments but formerly carried the principal drainage outlet from the upper Great Lakes. Spencer (1907, 1910) subsequently identified buried bedrock channels crossing the Niagara Escarpment that record the ancestral drainage between lakes Erie and Ontario. More recently, updated bedrock topographic maps of the study area have been published by White and Karrow (1971), Karrow (1973), Flint and Lolcama (1985), Eyles *et al.* (1985) and Eyles (1987).

As a result of rapid urbanisation many new data have become available with which to re-evaluate the form of the buried bedrock surface around the margins of Lake Ontario. Construction of a revised bedrock topography map for the present paper was facilitated using a new data archiving and analysis facility at the Scarborough Campus of the University of Toronto. The system comprises three dedicated PC-486 workstations with gigabyte capacity storage devices which incorporate a wide range of GIS, groundwater and terrain modelling and database management software packages. The primary data base used in this study comprises about 130 Mb of information consisting of a digital waterwell data set acquired from the Ontario Ministry of Environment. This comprises a total of over 300,000 water well records from southern Ontario having details of drift type, thicknesses and a wide range of hydrogeological information. These data are supplemented with more detailed subsurface data (*e.g.* stratigraphic, groundwater chemistry, etc.) collected during the course of landfill siting and other applied investigations in southern Ontario (*e.g.* Eyles *et al.*, 1992). Many data were provided in hard copy format (*e.g.* maps, reports) but digitally encoded data are increasingly available. The basis of the system is Intera Tydacs's SPANS (Spatial Analysis System) version 5.2; data can be uploaded directly from SPANS into digital terrain modelling packages such as SURFER.

The bedrock topography was mapped through a query of the central database performed with SPANS. The distribution across the study area of more than 70,000 bedrock wells located by the query is shown in Figure 4a. Due to the large size of the data set and the input limitations of numerical contouring methods, it was necessary to subdivide the study area into smaller equal area quadrants (25 × 25 km; Fig. 4b). Each of the quadrants were gridded within SURFER using a universal kriging algorithm with a 5 km boundary overlap, and a 200 × 200 grid line spacing to optimize the data resolution. Contoured quadrants were then exported and reassembled in AUTOCAD to produce the composite regional-scale map shown in Figure 5. Contour data were compared with existing bedrock topography maps and were revised by hand contouring where spurious values were created as a result of data inaccuracies or as artefacts of the machine contouring process (*e.g.* boundary effects). This analysis showed that although some well elevation data may show significant inaccuracies, their effect on a regional scale is outweighed by the large number of data. Dashed contours on Figure 5 represent limited data below the Oak Ridges Moraine where drift thicknesses are as much as 200 m (see below). It is emphasised that Figure 5 is provisional and will be updated as further data become available. The portion of New York State included in the present study is based on that published by Flint and Lolcama (1985) in their study of the Niagara Peninsula.

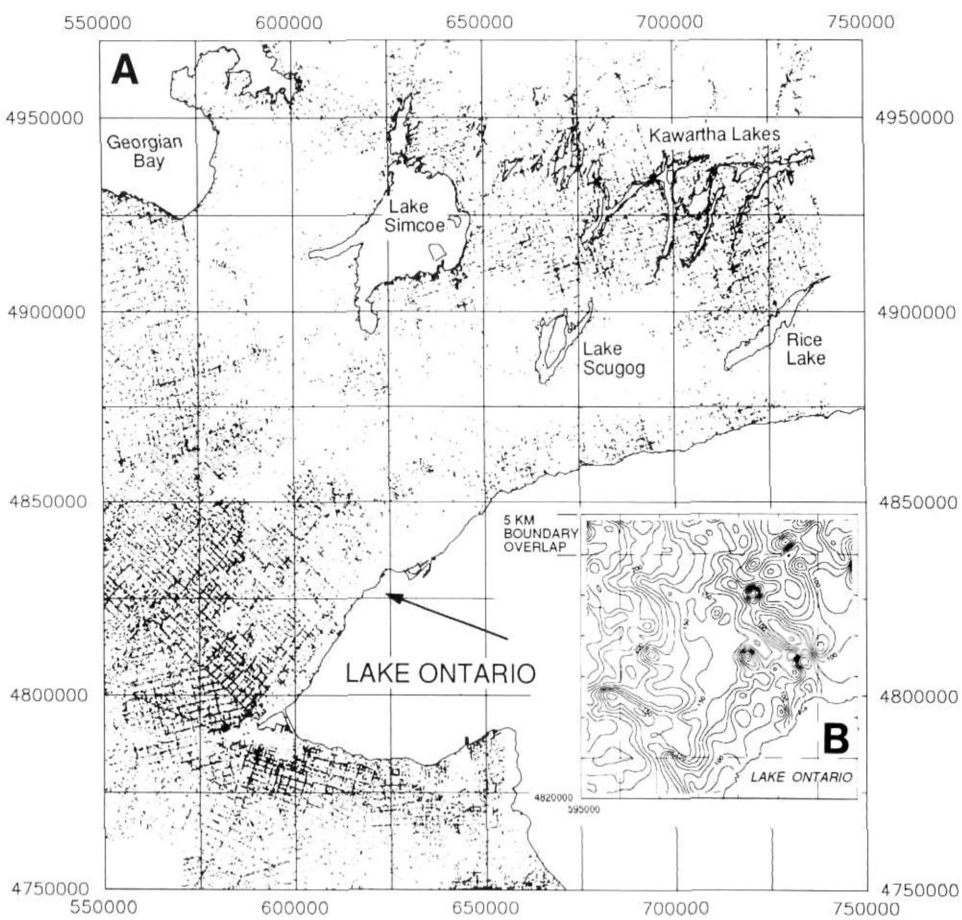

FIGURE 4. A) Distribution of more than 70,000 boreholes used to reconstruct the bedrock surface topography (Fig. 5). Area has been subdivided into equal area quadrants to facilitate numerical contouring. B) Example of machine gridded and contoured map of single quadrant area including western half of the Greater Toronto Area.

A) Répartition des plus de 70 000 trous de sondage qui ont servi à reconstituer la surface rocheuse (fig. 5). La région a été quadrillée afin de faciliter le tracé des courbes numériques. B) Détail d'un carré du quadrillage de la partie ouest de la zone métropolitaine de Toronto illustrant les courbes numériques produites par ordinateur.

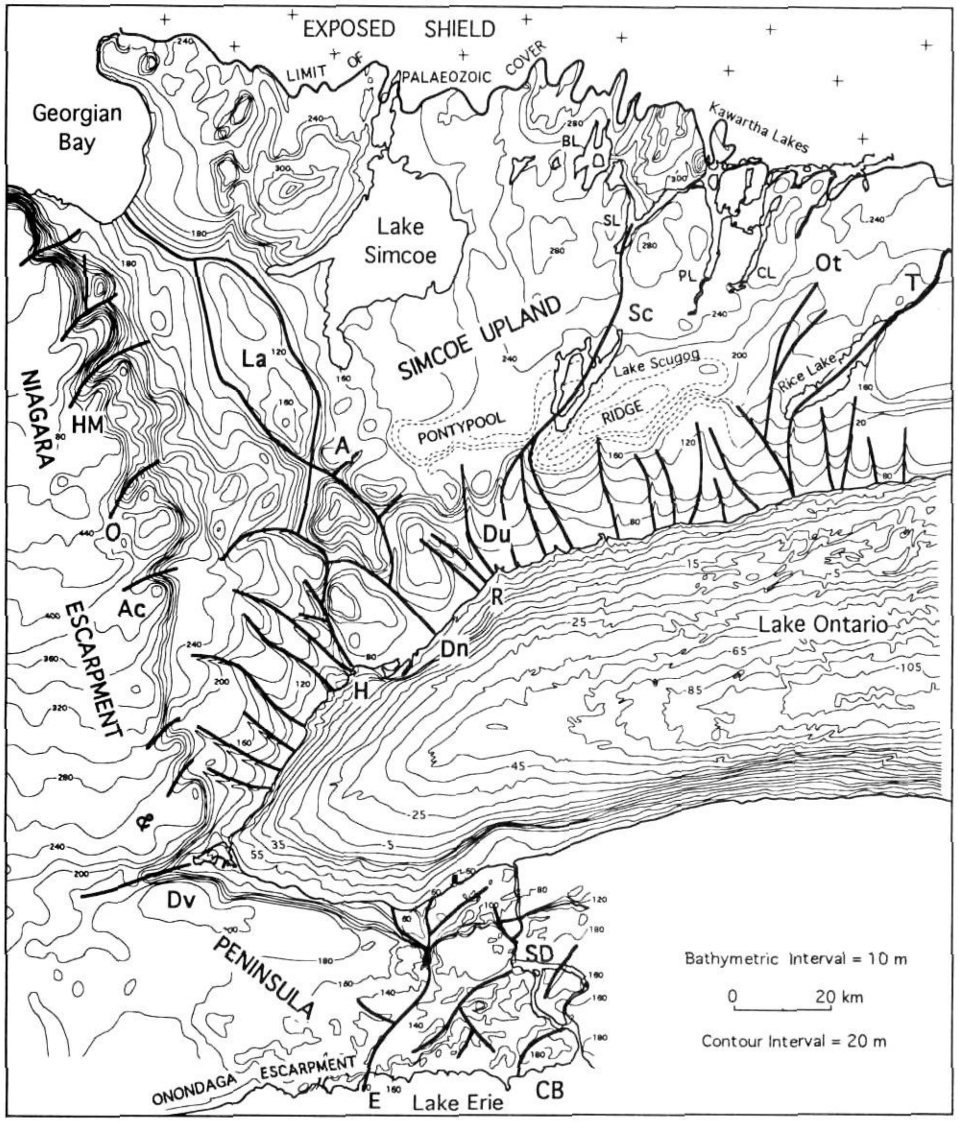

FIGURE 5. The sub-drift bedrock surface of the western Lake Ontario region reconstructed from depth to bedrock data. Dashed lines on bedrock contours indicate areas of limited data coverage. The bedrock surface shows several major channel systems: CB, Crystal Beach channel; Dn, Don channel; Du, Duffins Creek channel; Dv, Dundas valley; E, Erigan channel; H, Humber channel; La, Laurentian channel; Ot, Otanabee channel; R, Rouge River channels; RL, Rice Lake; Sc, Scugog channel; SD, St. Davids channel; T, Trent channel. Lakes named are: BL, Balsam Lake; CL, Chemung Lake; PL, Pigeon Lake; SL, Sturgeon Lake. The relationship of physiography to geological structure is shown in Figure 7. Other physiographic elements are the Niagara Escarpment, Onondaga Escarpment, the Simcoe upland and Pontypool ridge. Place names used in text are A, Aurora; Ac, Acton; HM, Horning's Mills; O, Orangeville.

La surface rocheuse sous les dépôts glaciaires de la partie ouest du lac Ontario reconstituée à partir des données numériques. Les courbes en tireté délimitent les zones où les données sont moins nombreuses. La surface rocheuse montre plusieurs réseaux importants de chenaux: CB, chenal de Crystal Beach; Dn, chenal Don; Du, chenal de Duffins Creek; Dv, vallée du Dundas; E, chenal Erigan; H, chenal Humber; La, chenal Laurentien; Ot, chenal Otanabee; R, chenaux de la rivière Rouge RL, Rice Lake; Sc, chenal Scugog; SD, chenal St. Davids; T, chenal Trent. Les lacs sont: BL, Balsam Lake; CL, Chemung Lake; PL, Pigeon Lake; SL, Sturgeon Lake. Les liens entre la physiographie et la structure géologique est illustrée à la figure 7. Les autres entités physiographiques sont les escarpements du Niagara et d'Onondaga, les hautes terres de Simcoe et la crête de Pontypool. A: Aurora; AC: Acton; HM: Horning's Mills; O; Ogangeville.

Data regarding the elevation of the bedrock floor below Lake Ontario are particularly scarce. To partly overcome this problem present day bathymetric contours were converted to elevations above mean sea level. This gives a crude approximation of the bedrock surface below the lake because thick sediment covers are restricted to the deep water basins toward the southern margin of the lake and off the mouth of the Niagara River (Martini and Bowlby, 1991). Elsewhere, bedrock is exposed over large areas and the bathymetry can be assumed to approximate the general form of the bedrock surface.

REGIONAL BEDROCK CONFIGURATION

The form of the regional bedrock surface in the western Lake Ontario region is shown on Figure 5. The most prominent bedrock topographic feature consists of an escarpment, with a relief of about 130 m (the Niagara Escarpment), extending from Georgian Bay to the Niagara Peninsula. The escarpment overlooks a shale-floored depression between Georgian Bay and Toronto. This depression has been referred to as either the Laurentian channel or Laurentian valley (Spencer, 1881, White and Karrow, 1971; Eyles, 1987) in recognition of its probable role as the main preglacial outlet of the Upper Great Lakes to the St. Lawrence River valley. The valley is infilled by Pleistocene glacial sediments.

The eastern margin of the Laurentian channel is not as well defined as the western margin and shows an eastward-rising bedrock surface informally named herein as the Simcoe upland (Fig. 5). This surface culminates to the north along the edge of Paleozoic cover rocks where mid-Proterozoic strata are exposed. A well-defined west-east trending bedrock cuesta (Pontypool ridge; Fig. 5) can be

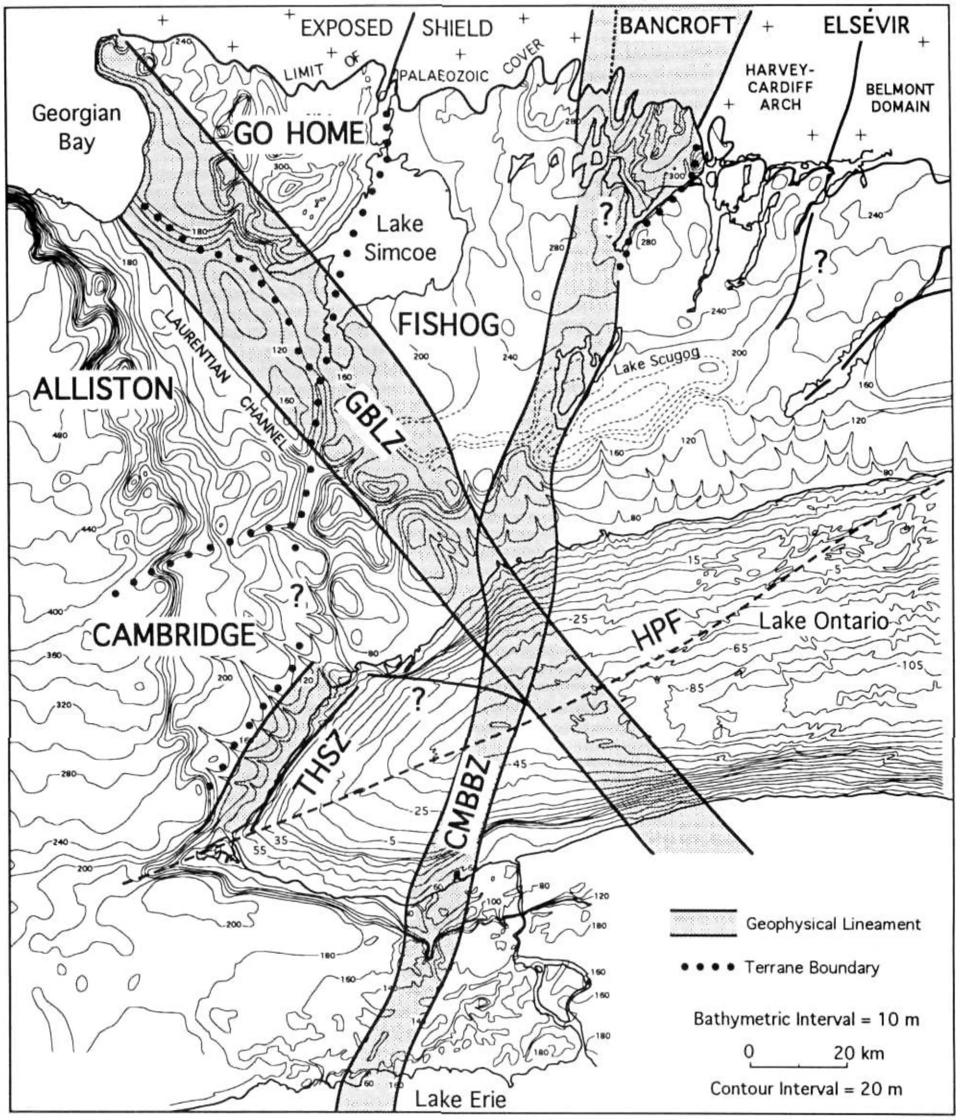

FIGURE 6. Bedrock surface map of south-central Ontario with mid-Proterozoic terrane boundaries (see Figs. 1-3), faults, principal aeromagnetic anomalies and other geophysical lineaments superimposed. THSZ, Toronto Hamilton seismic zone; GBLZ, Georgian Bay linear zone; HPF, Hamilton-Presqu'ile fault; CMBBZ, Central Metasedimentary Belt boundary zone. After sources named in text. See Figure 5 for named topographic and structural features.

Carte de la surface rocheuse dans le centre-sud de l'Ontario avec en superposition les limites des divisions du Protérozoïque moyen (fig. 1 à 3), les failles, les principales anomalies aéromagnétiques et les autres linéaments géophysiques. THSZ, zone sismique Toronto-Hamilton; GBLZ, zone linéaire de la Baie Georgienne; HPF, faille Hamilton-Presqu'île; CMBBZ, aire limite de la zone métasédimentaire centrale. Les sources sont données dans le texte. La figure 5 donne les noms des entités topographiques et structurales.

identified on the northern margins of the Lake Ontario basin. The offshore Lake Ontario basin shows a gently sloping northern margin and a much steeper southern margin.

DETAILED CHARACTERISTICS OF THE BEDROCK SURFACE

The bedrock surface (Fig. 5) shows a large number of narrow, deeply-cut linear channels. It is these channels and their geographic relationship with underlying middle Proterozoic faults, terrane boundaries and geophysical lineaments that forms the central focus of the present paper. For the ease of describing and interpreting these features the study area has been subdivided into four sectors viz., 1) the Laurentian channel; 2) Niagara Escarpment and Peninsula; 3) the Simcoe upland and 4) the Lake Ontario basin.

1) LAURENTAN CHANNEL

The Laurentian channel, together with the broader depression in which it is cut, has been excavated into westward-dipping shales belonging to the Late Ordovician Blue Mountain Formation (formerly the Whitby Formation of Liberty, 1969), the Georgian Bay Formation and the Queenston Formation (Johnson *et al.*, 1992). The subcrop of these units along the depression (Fig. 2) is approximate because of the extensive cover of Pleistocene drift. The Laurentian channel connects the Lake Ontario Basin with Georgian Bay and is underlain by a northwest/southeast trending zone of gravity and aeromagnetic lineaments called the Georgian Bay Linear Zone (GBLZ; Fig. 6), identified and named by Wallach and Mohajer (1990). The GBLZ extends from Parry Sound to Attica, New York where it joins the Clarendon-Linden fault associated with a $m_b = 5.2$ earthquake which occurred in 1929. The Laurentian channel was last occupied by a major southward draining river during the closing stages of the last (Sangamon) interglacial sometime after 100,000 years before present (Eyles and Williams, 1992; Berger and Eyles, 1994).

Within the shale-floored depression east of the Niagara Escarpment, the route of the Laurentian channel follows the boundaries of several terranes in the underlying Proterozoic basement (Figs. 5 and 6). Near Georgian Bay, the southwestern boundary of the Go Home terrane controls the westward-looping arm of Lake Simcoe and the uppermost portion of the Laurentian channel where it exits Georgian Bay. To the south, the Laurentian channel follows the boundary between the Go Home, Alliston, Cambridge and Fishog terranes (Figs. 5 and 6). In addition, the northeast trending boundary between the Cambridge and Alliston terranes in the middle Proterozoic basement controls the position of a tributary valley of the Laurentian channel.

The Laurentian channel has an 'up and down' long profile typical of glacially-modified fluvial valleys. Along the deepest part of the Laurentian channel system, the lowest elevation along the bedrock floor lies close to sea level. Toward Lake Ontario, the Laurentian channel splits into two channels previously identified as the Humber and Don channels (see Eyles, 1987) parallel to the present day Humber and Don rivers (Fig. 5).

2) NIAGARA ESCARPMENT AND PENINSULA

The Niagara Escarpment shows several deeply-cut bedrock re-entrants having a consistent northeast trend. The origin and significance of these valleys has been discussed by several workers (Straw, 1968; Smith and Legault, 1985; Gross and Engelder, 1991). Especially prominent are the deep valleys at Horning's Mills, those near Orangeville and Acton and the Dundas valley at the western end of Lake Ontario (Fig. 5). The last named coincides with the Hamilton-Presqu'ile fault (Ontario Geological Survey, 1991) trending northeast subparallel to the long axis of Lake Ontario (HPF; Fig. 6).

The northeast trend of buried bedrock valleys along the Niagara Escarpment is maintained over 200 km from Georgian Bay in the north to the Niagara Peninsula. The gross form of the buried bedrock surface along the peninsula reflects the southward dip of Paleozoic strata and the presence of two subdued escarpments (the Niagara and Onondaga) largely buried below Pleistocene sediments. These escarpments are cut by several prominent bedrock channels, such as the Erigan channel, the Crystal Beach channel in the vicinity of Niagara Falls, and the St. David's channel (Fig. 5). The form of these channels and the implications for the drainage history of the Great Lakes have been described by Flint and Lolcama (1985).

A well-defined NW and NE alignment of bedrock channels along the length of the Niagara Peninsula is clearly evident from Figure 5; Flint and Lolcama (1985) briefly commented on, but did not further pursue, the strong influence of bedrock jointing on the orientation of bedrock valleys. The strongly developed NW and NE alignment of joints on the Niagara Peninsula has been noted by Johnson (1964), Scheidegger (1977), Williams *et al.* (1985), Sanford *et al.* (1985), Novakowski and Lapcevic (1988), Daniels (1990) and Gross *et al.* (1992) and is discussed further below.

The position of the Erigan channel system is of particular significance as it lies parallel with the conspicuous Niagara-Pickering Linear Zone (Wallach and Mohajer, 1990) of gravity and aeromagnetic anomalies that identify the Central Metasedimentary Belt Boundary Zone (CMBBZ) where it crosses Lake Ontario and the Niagara Peninsula (Figs. 3, 6, 7). This structure extends from western Québec to northern Ohio where it is associated with seismic activity along the Akron magnetic boundary (*e.g.* 1986 LeRoy, Ohio earthquake; $m_b=4.9$).

3) SIMCOE RISE

This sector includes that area of south-central Ontario above the 160 m elevation that lies to the northeast of the Laurentian channel and the Lake Ontario basin (Fig. 5). The area is distinguished by the present day basin of Lake Simcoe and a number of northeast trending 'finger' lakes (the Kawartha lakes; Scugog, Rice, Pigeon, Sturgeon and Chemung; Fig. 5). The area is underlain by Middle Ordovician carbonates (Fig. 2) dipping gently to the southwest (Johnson *et al.*, 1992). These strata contain thin shales and differential down-dip erosion has resulted in gentle cuestas and strike vales now blanketed by glacial sediments. Drift thickness is greatest (up to 200 m) in a west-east trending belt of glacial deposits (the Oak Ridges Moraine) (Chapman, 1985). Few wells reach bedrock in this area (Fig. 4) and the form of the underlying bedrock surface is not known in detail (Fig. 5). The moraine ridge lies on top of a bedrock high (Pontypool ridge; Fig. 5) which reflects the presence of alternating shales and limestones in the Verulam and Lindsay formations (Fig. 2).

The Pontypool ridge is punctured by a prominent northeast trending valley (the Scugog channel; Fig. 5), forming a distinct topographic low now occupied in part by Lake Scugog. The channel reaches a maximum width of 10 km and gives rise to a southward-closing erosional reentrant in the strike of Upper Ordovician shales. The Scucog channel is aligned along the underlying CMBBZ basement structure (Figs. 5 and 6) that can be traced southward toward Lake Ontario where it underlies several closely-spaced bedrock valleys (*e.g.* Duffins Creek valley; Fig. 5). Other buried bedrock valleys (*e.g.* Otonabee and Trent channels; Fig. 5) can be traced to the northeast where they continue as the shallow bedrock-floored finger lakes (*e.g.* Sturgeon, Pigeon, Chemung lakes) that occupy re-entrants cut into the northern edge of the Paleozoic cover (Figs. 5 and 6). The position of the lakes can be related to the SSW-trending strike of terrane and sub-terrane boundaries in the underlying basement below the Paleozoic cover and which are clearly exposed to the north beyond the limit of cover rocks (Figs. 3 and 6).

4) LAKE ONTARIO BASIN

The northern margin of the Lake Ontario Basin comprises a gently sloping bedrock surface incised by narrow bedrock valleys. These valleys maintain a distinct northwest trend between the western end of Lake Ontario and the eastern limit of the study area and are incised into Upper Ordovician Whitby and overlying Queenston Formation shales (Fig. 5). The Duffins Creek channel and neighbouring valleys immediately to the east represent a southward extension of the Scugog channel aligned along the CMBBZ (Figs. 6 and 7).

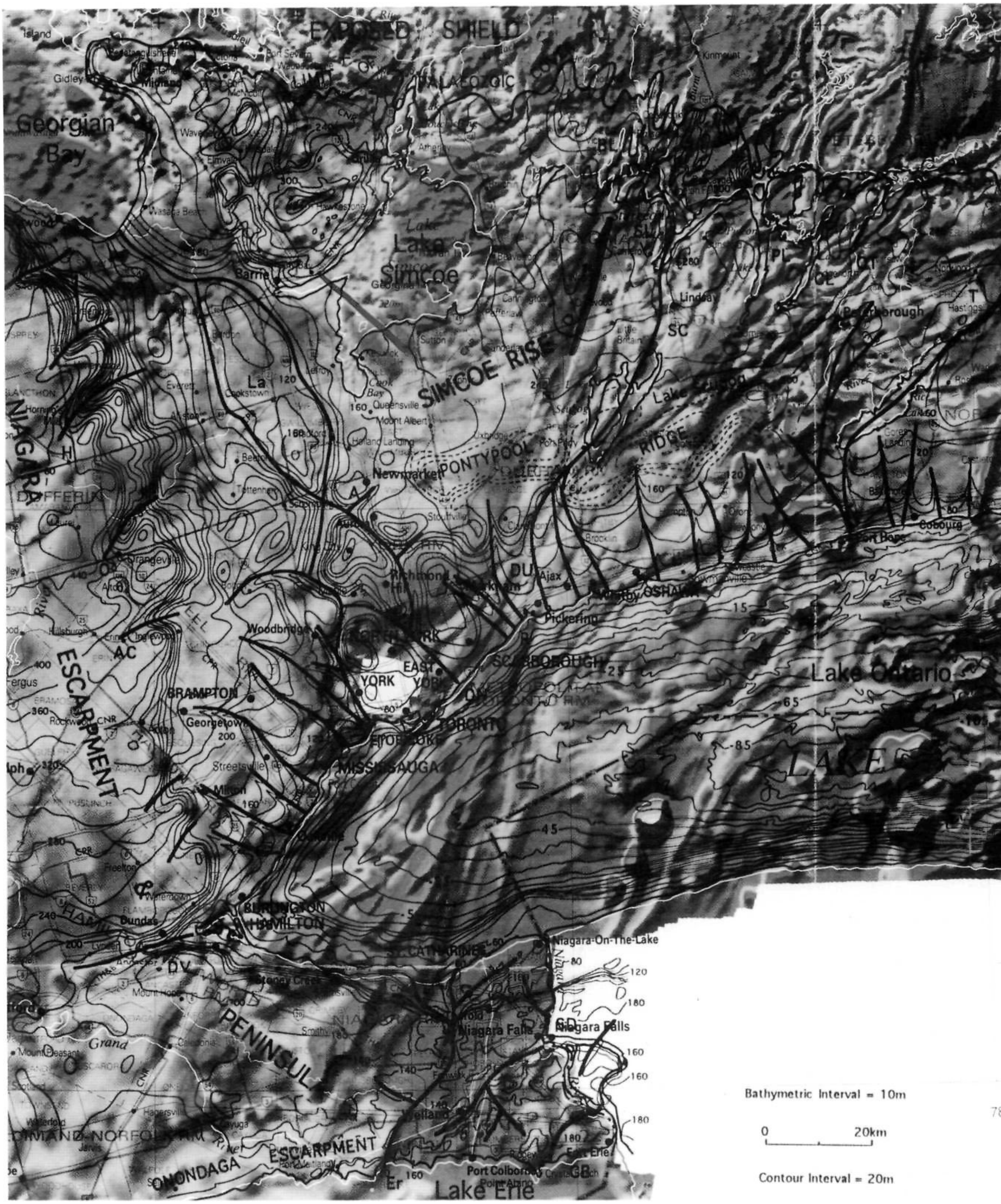

FIGURE 7. Bedrock surface (Fig. 5) superimposed on shaded relief image of residual total magnetic field map of south-central Ontario (Gupta, 1991b). Aeromagnetic anomalies are enhanced by a sun angle of 35° with an azimuth of 320°. Note relationship between Central Metasedimentary Boundary Zone (see Fig. 6) and northeast trending bedrock channels cut across the Niagara Peninsula and in the vicinity of Lake Scugog, where the Pontypool ridge is punctured by a prominent channel, and the Kawartha lakes (see Fig. 5). See Figure 5 for named topographic features.

Surface rocheuse (fig. 5) surimposée à une carte en relief ombragé du champ magnétique global du centre sud de l'Ontario (Gupta, 1991b). Les anomalies aéromagnétiques sont soulignées par un angle du soleil à 35° et azimut à 320°. Noter les liens entre l'aire limite de la zone métasédimentaire centrale (fig. 6) et l'orientation nord-est des chenaux du socle qui entaillent la péninsule du Niagara et les alentours du Lake Scugog, où la crête de Pontypool est percée par un important chenal, et les lacs Kawartha (fig. 5). La figure 5 donne les noms des entités topographiques.

Offshore, the CMBBZ cannot, given the quality of the present offshore data base, be readily identified as a major topographic feature on the floor of Lake Ontario.

A linear magnetic anomaly, originally named the Hamilton-Presqu'ile lineament by McFall and Allam (1991), extends beneath Lake Ontario in an east-northeast direction from Hamilton to the northern shoreline of the lake near the eastern boundary of the study area. The Ontario Geological Survey (1991) labelled this feature a fault, but did not draw it as far west as Hamilton. Subsequently referred to as the Hamilton-Presqu'ile fault (HPF) by McFall (1993), this feature appears to have bathymetric expression as well. In the western part of Lake Ontario this takes the form of a linear valley, marked by the locus of points of greatest curvature on the bathymetric contours and the tip at the western end of Lake Ontario (Figs. 5 and 6), which coincides with the Dundas Valley; in the eastern part of the study area it is expressed as a pronounced lineament about 25 km long which is located between the words *Lake Ontario* and the north shore of the lake (Figs. 5 and 6).

RELATIONSHIP BETWEEN BASEMENT STRUCTURE AND THE BEDROCK SURFACE IN SOUTH-CENTRAL ONTARIO

The age of the bedrock surface in south-central Ontario is not known, but is commonly thought to be Late Tertiary or 'pre-glacial' in age. Presumably the topography results from long term fluvial erosion, mass wasting along the margins of steep slopes and, in the Pleistocene, by glacial erosion below successive North American ice sheets. The extent of landscape modification by any one of these processes is not clear. It is apparent, however, that erosion of this topography has been strongly influenced by middle Proterozoic basement structures and regional joint sets in Paleozoic strata.

BASEMENT STRUCTURES

A major influence on the development of the bedrock surface around the margins of Lake Ontario appears to have been the presence and location of middle Proterozoic basement structures below the Paleozoic cover. The most prominent regional structure is the boundary zone between the Central Gneiss Belt and the Central Metasedimentary Belt (CMBBZ). This broad zone comprises cataclastic and tectonised quartzofeldspathic gneisses dipping to the southeast at between 20° to 40° (Easton, 1992). The position of this belt is clearly expressed in the topography of the Niagara Peninsula (the Erigan channel system; Figs. 5 and 6) and north of Lake Ontario as the Duffins Creek channel and the Scugog channel where it crosses the Pontypool ridge. The CMBBZ broadens northward below Sturgeon Lake and merges with the Bancroft terrane; preliminary LITHOPROBE seismic data show these are seismically inseparable and form a single tectonic zone (Easton, 1992). The eastern limit of the CMBBZ-Bancroft tectonic zone appears to be defined topographically by the northeast arm of Lake Scugog hence passing northward along the east shore of Sturgeon Lake (Figs. 5-7).

The Central Metasedimentary Belt is structurally complex and this is reflected in the topography of the eastern part of the Simcoe upland. There, the Otonabee channel lies along the trend of the intensely sheared boundary between the Harvey-Cardiff arch and Belmont domain within the Elzevir terrane (Figs. 5 and 6). Elsewhere in the CMB the subcrop of basement structures below the Paleozoic sequence is not well known and it is not yet possible to relate the remainder of the Kawartha finger lakes (Pigeon, Chemung) to specific basement structures. Nonetheless, it is very noticeable that the axes of the lakes are aligned along the strike of aeromagnetic lineaments in that area (Figs. 5 and 6). The Ontario Geological Survey (1991) shows a basement structure passing southwestward below Rice Lake and the Trent channel (Figs. 5 and 6) suggesting a structural alignment.

Within the Central Gneiss Belt, the boundaries between the Alliston, Go Home, Fishog and Cambridge terranes coincide with, and appear to control the position of, the Laurentian channel between Georgian Bay and Lake Ontario (Figs. 5 and 6). Topographic control by the Georgian Bay linear zone is less clear. The GBLZ is about 25 km wide and consists of closely-spaced, southeasterly trending gravity and aeromagnetic lineaments (Wallach, 1990; Wallach and Mohajer, 1990; Gupta, 1991a, b). The origin and geological significance of this zone is as yet not well known but the geographic association with the Laurentian channel and the associated bedrock depression suggests a causal link. The position of the Hamilton-Presqu'ile fault (HPF) is expressed on the floor of Lake Ontario and underlies the large re-entrant valley (Dundas Valley) at the western end of Lake Ontario (Figs. 5 and 6).

REGIONAL FRACTURE SETS

A second structural control on the bedrock surface is that exerted by a well defined northeast and northwest directed regional fracture system and was first recognised by Wilson (1901). Buried bedrock valleys commonly show a strongly preferred orientation along either one or both of these trends producing a distinctly trellised or reticulate drainage pattern (*e.g.* Scheidegger, 1980, 1982; Fig. 5). Published work demonstrates, with some local variation, the predominance of northeast and northwest trending fractures over a wide area of eastern North America extending from the Appalachian Plateau to Ontario (*e.g.* Scheidegger, 1977, 1980; Sanford *et al.*, 1985; Engelder, 1982; Hancock and Engelder, 1989; Daniels, 1990; Gross *et al.*, 1992; Rogojina, 1993).

Gross *et al.* (1992) argued that NW trending fractures in eastern North America are related to Alleghanian deformation at about 300-250 Ma. In contrast, NE trending joints were regarded as 'neotectonic' (*i.e.* post-Miocene; Slemmons, 1991) in age, reflecting the modern mid-continent stress field. Those fractures in the present study area have been ascribed to load-parallel stress-release under high horizontal compressive stresses (Hancock and Engelder, 1989; Mohajer *et al.*, 1992). The core of this argument is that regional uplift and denudation results in tensile stresses in near-surface strata. When superimposed on the regional direction of compressive stress, tension fractures are produced parallel to the regional direction of maximum horizontal compressive stress (Stauffer and Gendzill, 1987; Lorenz *et al.*, 1991). It should be noted that Scheidegger (1991, 1993) regarded fractures in the region as shear structures but this has been disputed (Hancock and Engelder, 1991). Regardless, these workers have agreed that fractures are systematically related to the current neotectonic stress field. The direction of maximum horizontal compressive stress in the study area is oriented northeast/southwest (Adams and Basham, 1991; Gross and Engelder, 1991; Gross *et al.*, 1992) and is the result of the absolute plate motion direction of North America (Zoback, 1992). Given, however, that the same stress field may have obtained in mid-continent since the Late Jurassic-Early Cretaceous opening of the Atlantic Ocean (*e.g.* Tankard and Balkwill, 1989), it is suggested here that the NE trending 'neotectonic' fracture sets could be much older than suggested by Gross *et al.* (1992). Miller and Duddy (1989) for example, identified a major uplift event across the northern Appalachian Basin during the Early Cretaceous between 140 and 120 Ma, and which may have had a major effect on the state of stress and development of fractures in near surface strata.

Figure 5 shows that the bedrock valleys cut into Ordovician strata stratigraphically *below* the Niagara Escarpment have a predominant northwest trend. In contrast, a northeast trend is clearly preferred by those valleys cut into younger Silurian and Devonian strata *along* the escarpment (Figs. 2 and 5). These two sets of strata (equivalent to depositional sequences 3 and 4 of Johnson *et al.*, 1992) are separated by an unconformity surface resulting from a Late Ordovician sea level regression. The orientation of buried bedrock valleys (Fig. 5) suggests that the direction of fracturing is lithologically controlled and varies from the Ordovician depositional sequence to the Silurian-Devonian sequence. However, this relationship is not seen across the Niagara Peninsula where both fracture directions obtain.

STRUCTURAL CONTROLS IN INTRACRATONIC BASINS

Traditional views of the structural history of intracratonic basins emphasise tectonic stability, thermal 'sagging' and the deposition of simple, conformable successions of cover strata. New work highlights the importance of faulting and abrupt thickness and facies changes caused by Phanerozoic reactivation of Proterozoic crustal structures (Leighton, 1990). The driving mechanism appears to be variation in the magnitude and direction of mid-continent intraplate stresses generated at distant plate margins (Sanford *et al.,* 1985; Sanford and Smith, 1987; Klein and Hsui, 1987; Cloetingh, 1986, 1988; Mollard, 1988: Leighton and Kolata 1990; Leighton *et al.*, 1990; Eyles and Eyles, 1993); global-scale plate tectonic reorganisations give rise to episodic, but cosympathetic, subsidence from one basin to another producing large-scale stratigraphic sequences that are globally synchronous (*e.g.* Sloss, 1963, 1972, 1988 a, b).

Recent studies of cratonic and pericratonic basins in mid-continent North America (*e.g.* Appalachian, Williston, Michigan, Illinois basins), demonstrate the presence of highly-faulted and complexly structured Proterozoic basement (Leighton *et al.,* 1990). Reactivated Proterozoic structures exert a strong control on subsequent Phanerozoic basin configurations, sedimentation patterns, depositional facies and the areal pattern of oil and gas reservoirs and hydrocarbon trapping mechanisms (*e.g.* Sanford *et al.*, 1985; Klein and Hsui, 1987; Catacosinos and Daniel, 1990; Leighton and Kolata, 1990; Heigold, 1990; Daly *et al.*, 1991). Mollard (1988) showed how deeply seated basement structures, and associated regional fracture patterns, control geological, hydrogeological and geochemical processes even in Pleistocene sediments. Sanford *et al.* (1985) suggested that large areas of the North American craton were intermittently active throughout the Paleozoic.

Deeply buried basement structures act essentially as a 'template' for the Phanerozoic structural and depositional history of cratonic basins. With regard to the Ontario portion of the Michigan and Appalachian basins, the continued influence of basement structures during the Phanerozoic has been clearly shown for the area between lakes Huron and Erie. The thicker Paleozoic strata west of this area (*e.g.* Fig. 1) have been exhaustively explored for oil, gas and evaporites. Employing a wealth of subsurface data obtained from hydrocarbon exploration, together with Landsat imagery, Sanford *et al.* (1985) and Middleton *et al.* (1990) demonstrated the importance of Phanerozoic fracture systems, created by reactivation of underlying Proterozoic structures, in controlling hydrocarbon traps in Cambrian to Devonian strata. These workers identified linear trends in reservoir geometry resulting from the preferential growth of carbonate reefs on the up-tilted margins of fractured blocks. Fractures also controlled the movement of dolomitized fluids creating linear collapse features in evaporites and zones of enhanced porosity in carbonates. In turn, these processes subsequently controlled the formation and geometry of hydrocarbon reservoirs. Regional fracturing was attributed to episodic uplift and forebulging of the Findlay-Algonquin arch in response to collisional events along the eastern continental margin of North America (see below).

Smith and Legault (1985) studied Silurian reef complexes (biohermal mounds) in the Amabel and Guelph formations exposed along the Bruce Peninsula and Niagara Escarpment. They identified a well-defined preferred alignment of reef long axes with a northeast-southwest alignment for Guelph reefs and a predominant northwest-southeast trend for Amabel reefs. These directions were related by Smith and Legault to the direction of the then prevailing winds and tides. It is suggested here that an alternative explanation for the preferred directions of reef growth might have been the same structural control by reactivated basement structures identified by Sanford *et al.* (1985) in southwestern Ontario.

Reactivation of Proterozoic basement structures as a major control on the tectonic development of Phanerozoic intracratonic basins is now widely accepted (see Leighton and Kolata, 1990 for review). Recurrent basement-propagated faulting is recognised to be an inherent characteristic of such basins; present emphasis lies on identifying the different broad-scale tectonic mechanisms that may result in basement reactivation. The subsurface work of Sanford *et al.* (1985) from west of the Niagara Escarpment and the data reported herein provide strong support for this structural model in southern Ontario.

MECHANISMS OF BASEMENT REACTIVATION IN THE WESTERN LAKE ONTARIO REGION

Reactivation of basement structures in southwestern Ontario accompanied uplift of the Findlay-Algonquin Arch (Sanford *et al.*, 1985). Uplift is most likely to have occurred in response to crustal loading by successive Phanerozoic orogenies along the eastern margin of the North American craton (Quinlan and Beaumont, 1984; Sanford and Smith, 1987). The arch may essentially act as a peripheral bulge defining the far northern margin of the Appalachian foreland basin. In support of this model, recent reviews of the Paleozoic geology of southern Ontario by Johnson *et al.* (1992) have identified a number of unconformity-bounded depositional sequences that can be related to episodic uplift of the arch and subaerial erosion, alternating with subsidence of the arch and renewed sediment accumulation.

Episodic 'arching' in southern Ontario has been accomplished by uplift and tilting of discrete basement blocks separated by sharply defined crustal discontinuities (Sanford *et al.*, 1985). The most prominent basement structure of the region is the CMBBZ and seismic refraction profiles across part of the Grenville Province reveal steeply dipping structures and pronounced changes in crustal thickness either side of this structure (Milkereit *et al.*, 1992; Easton, 1992). In turn, the CGB and CMB are composed of smaller terranes each bounded by narrow, highly deformed boundary zones (Easton, 1992). It is possible that these blocks have moved relative to each other during the Phanerozoic, in the fashion of piano keys, in response to changing crustal loads caused by the Appalachian Orogeny and changing intra-plate stresses across mid-continent North America. In this way, fractures may have propagated upwards into cover strata resulting in structurally-aligned linear valleys cut on the surface of Paleozoic strata (Fig. 8).

Within the last 2.5 Ma, south-central Ontario and adjacent New York State have been subjected to repeated Pleistocene glaciations and associated processes of crustal depression and rebound accompanying ice sheet growth and decay (Kite, 1972). During each glacial cycle there is crustal flexing associated with ice sheet thickening, the development and outward migration of a forebulge and its inward collapse as the ice sheet eventually thins (*e.g.* Vanicek and Nagy, 1980; Andrews, 1987, 1991). Accelerated incidence of earthquakes in the early postglacial, *i.e.* at a time of very rapid crustal rebound, has been suggested for many glaciated areas Mreflecting differential recovery across faults (Oliver *et al.*, 1970; Adams, 1989; Mörner *et al.*, 1989; Lägerback, 1990; Andrews, 1991). James and Morgan (1990) have also identified near surface crustal shortening during rebound which could lead to reactivation of old structures. Presumably the same effects occur during ice sheet growth and crustal depression. By analogy with the induced seismicity created by reservoirs (*e.g.* Knoll, 1992), structural reactivation and seismic activity may also be promoted in the study area by very substantial changes in elevation (100 m; Eyles and Williams, 1992) in the level of the ancestral Lake Ontario caused by successive Pleistocene ice dams along the St. Lawrence River valley. All these various processes could give

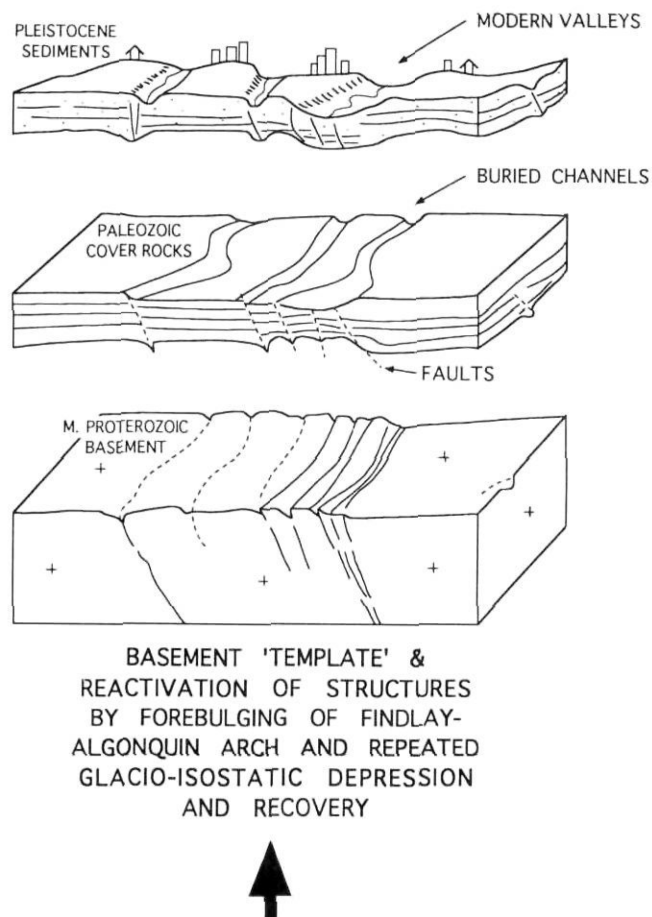

FIGURE 8. *Tentative* model for development of bedrock surface topography in south central Ontario involving reactivation of mid-Proterozoic Grenville basement structures. Reactivation may result from forebulging of Findlay-Algonquin arch in response to changing intra-plate stresses caused by Phanerozoic collisional tectonic events along the eastern margin of North America. Long term Phanerozoic erosion and uplift combined with repeated crustal depression and rebound accompanying Pleistocene glaciations may also promote differential movement along basement structures (see text). Regional joint sets not shown.

Modèle provisoire de l'évolution de la surface rocheuse au centre-sud de l'Ontario impliquant la réactivation des structures du socle grenvillien du Protérozoïque moyen. La réactivation est peut-être le résultat du soulèvement de l'arc Findlay-Algonquin en réponse à des changements dans les contraintes issues de l'intra-plaque, entraînés par les collisions tectoniques le long de la marge orientale de l'Amérique du Nord. L'érosion et le soulèvement répartis sur une longue période au Phanérozoïque combinés aux affaissements et relèvements répétés de l'écorce au cours des glaciations du Pléistocène a pu également provoquer des mouvements différentiels le long des structures du socle (voir texte).

rise to preferential erosion of fractured Paleozoic strata overlying reactivated basement structures.

DISCUSSION

It has been proposed above that basement structures and joints have influenced the topography cut on the upper surface of Paleozoic strata. In turn, it should be noted that these structures also appear to have exerted a strong influence on the modern day drainage system. Modern river valleys, underlain by many tens of metres of Pleistocene sediment, often lie directly above buried bedrock valleys. Scheidegger (1980) analysed the trends of modern valleys in southern Ontario and found systematic northwest and northeast trends which he related to the modern mid-continent stress-field and the trend of regional fracturing. The presence of a pervasive, well-developed fracture set in Pleistocene sediments of the Toronto area was identified by Daniels (1990), MacLaren Plansearch (1990) and Livingstone (1991); these studies, together with recent measurements of fractures in the floors of deep (7 m) test pits dug into Pleistocene tills (Eyles, unpub. data), identified the same northeast and northwest trending fracture system as present in underlying Paleozoic bedrock suggesting upward, postglacial propagation from underlying bedrock. This is clearly a topic for further research.

The data (Figs. 5 and 6) and provisional model (Fig. 8) presented in this paper are of particular importance to the discussion of the present day structural stability of the Lake Ontario region. The potential of buried basement structures to generate damaging earthquakes is the subject of intense discussion (Adams and Basham, 1991; Wallach and Mohajer, 1990; Mohajer, 1991, 1993; Mohajer *et al.* 1992). This is not the place to enter into a full discussion of the regional seismotectonic framework except to emphasise that the western end of Lake Ontario shows a distinct clustering of earthquake epicentres that are spatially correlated with basement structures such as the CMBBZ/NPLZ. Of special interest is the Toronto-Hamilton Seismic Zone (THSZ) which is a broad, linear zone of concentrated microearthquake activity extending north-northeastward parallel to the northwestern shoreline of Lake Ontario (Mohajer, 1993; Fig. 6). This zone constrains most of the earthquakes that have occurred at the western end of Lake Ontario during the present century (Mohajer, 1993). The zone coincides with the northeast striking and southwest dipping boundary of the Cambridge and Fishog terranes within the underlying basement. The depth distribution of instrumented earthquakes shows that more than half of the recorded events fall within the mid-crustal section, between 5 and 20 km deep (Mohajer, 1993) indicating that such earthquakes are the expression of deep-seated activity along basement structures. To the east, the aeromagnetic lineament that demarcates the Hamilton-Presqu'ile fault is spatially correlated with several earthquakes along the northern shore of Lake Ontario (Mohajer, 1993).

It seems reasonable to suggest that the relationship between basement structure and drainage systems cut across Paleozoic cover strata around the western end of Lake Ontario, may be the expression of episodic reactivation of deeply-seated Proterozoic structures (Fig. 8). Henceforth, it is important to determine whether such a structural relationship is the result of successive cycles of glacio-isostatic depression and rebound and was confined to the Pleistocene. Future research should focus on the age of the erosional topography identified herein and identification of structures in Paleozoic strata indicating pre-Pleistocene structural activity.

In the light of the data presented above, combined with understanding of the structural history of other cratonic basins (*e.g.* Sanford *et al.*, 1985; Leighton and Kolata, 1990), the hitherto accepted assumption of the Phanerozoic structural stability of southern Ontario and adjacent New York State should be questioned. In a regional review of the geophysical framework of eastern mid-continent North America, Barosh (1986) emphasised the importance of Late Cenozoic seismicity generated by the reactivation of pre-Cenozoic faults. He also stressed the difficulty of recognising Cenozoic faulting given the absence, in many areas, of any stratigraphic record of this time interval. Investigation of the sub-drift surface in other areas of mid-continent, together with comparison with non-glaciated bedrock surfaces outside the limit of Pleistocene glaciations, would be a valuable exercise.

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