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STRUCTURAL ELEMENTS AND NEOTECTONICS OF PRINCE EDWARD COUNTY, SOUTHERN ONTARIO

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ABSTRACT The seismically active Clarendon-Linden Fault of western New York State appears to connect with the Salmon River Fault and possibly with the Picton Fault, both of which cut through Prince Edward County, southern Ontario. Bedrock exposures display a variety of structural features including faults, fractures, and pop-ups which indicate that the region has been subjected to repeated tectonism since the Middle Ordovician. Thus, despite the general perception that Prince Edward County and the rest of the Lake Ontario region is one of low seismic potential, geological and geophysical data suggest otherwise.

RÉSUMÉ *Les éléments structuraux et la néotectonique dans le comté de Prince Edward, au sud de l'Ontario.* La faille sismiquement active de Clarendon-Linden dans l'ouest de l'État de New York semble être reliée à la faille de Salmon River et probablement à la faille de Picton, qui traversent toutes deux le comté de Prince Edward. Les affleurements laissent voir une variété de formes structurales, comprenant des failles, des fractures et des soulèvements qui démontrent que la région à été tectonisée depuis l'Ordovicien moyen. Ainsi, même si l'on croit généralement que le comté de Prince Edward et l'ensemble de la région du lac Ontario est une zone de faible sismicité, les données géologiques et géophysiques donnent des indications contraires.

ZUSAMMENFASSUNG *Strukturelle Elemente und Neotektonik des Prince Edward-Bezirks, südliches Ontario.* Die seismisch aktive Clarendon-Linden-Verwerfung im Westen des Staates New York scheint mit der Salmon River-Verwerfung und möglicherweise mit der Picton-Verwerfung, die beide den Prince Edward-Bezirk durchqueren, verbunden zu sein. Die Aufschlüsse anstehenden Gesteins bestehen aus einer Vielfalt struktureller Formen wie Verwerfungen, Brüche und Hebungen, welche zeigen, daß die Region seit dem mittleren Ordovicium wiederholter Tektonik ausgesetzt war. Trotz der allgemeinen Annahme, daß der Prince Edward-Bezirk und der Rest der Ontario-See-Region ein niedriges seismisches Potential hat, belegen so geologische und geophysikalische Daten das Gegenteil.

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INTRODUCTION

GENERAL STATEMENT

In Canada the evaluation of seismic risk and seismic hazard are often based, to a large degree, upon existing seismic data. There is an inherent shortcoming to this method because records of seismicity have only been collected for the past 200-300 years. The geologic record, which is much older than the documented seismic record, can be examined for evidence of past tectonic instabilities and, therefore, has the potential to provide a more representative picture of the seismic potential of an area. For example, Tuttle *et al.* (1990), while examining liquefaction features in the Ferland area of Québec, determined that a major seismic event affected that area 600 years ago.

Southern Ontario has classically been considered a stable region because of the apparent lack of large-scale deformational features, major faults and major seismicity. This perception may also be attributed to the concept of the "stable craton" which underlies the Paleozoic succession. Sanford *et al.* (1985) challenged this perception in a paper which established a fracture framework for southwestern Ontario and reconstructed movements of the fractures in response to tectonism during the Phanerozoic. This prompted a re-examination of existing data and the undertaking of new studies to evaluate neotectonic conditions in southern Ontario. The collection of new information on southern Ontario began in 1987 with the detailed mapping of structural features in the southern part of Prince Edward County. Prince Edward County was chosen primarily because it is cut by at least two major faults of which one, possibly both, connect with the seismically active Clarendon-Linden Fault in New York State, USA (Fakundiny *et al.*, 1978a, b). Despite the presence of these faults, however, Prince Edward County is not known to have been the site of any major seismicity.

OBJECTIVE

The objective of this paper is to describe the tectonic framework of Prince Edward County, based largely on mesoscopic-scale structures, and discuss the role of the various structures in the context of neotectonics. For the purpose of this paper, neotectonic processes are defined as those which have occurred since the retreat of the last glacial ice sheet, which was about 12,000 years ago (Fullerton, 1980). Although the emphasis of this paper is on mesoscopic-scale bedrock structures, large-scale faults and geophysically expressed lineaments occurring both within, and outside, the study area have also been addressed because of their relevance to the understanding of the seismic potential of Prince Edward County.

PREVIOUS WORK

Both bedrock and surficial deposits have been studied in Prince Edward County. Kay (1937, 1942) mapped the Paleozoic stratigraphy of the area and identified a group of northeast trending monoclines. Liberty (1960) subdivided Kay's major stratigraphic units and identified several of the monoclines as faults. Carson (1980, 1981b, 1982) confirmed and updated Liberty's stratigraphy, Williams and Trotter (1984) evaluated the bedrock and surficial deposits from a hydrogeologic perspective, and McFall and Allam (1990, 1991) studied the age and origin of mesoscopic-scale structures in the Paleozoic bedrock.

Gadd (1980) evaluated the late-glacial ice-flow patterns that crossed Prince Edward County toward the west-southwest. Leyland (1982, 1983, 1984) mapped the distribution of the Quaternary deposits in the region, and Gorrell (1988) studied the age and origin of features in Quaternary deposits in southern Prince Edward County. Creasy (1976), from a study of aerial photographs, recognized a number of features including sinkholes, domes, folds, dykes and faults. Using false-colour infrared aerial photographs, Bowlby *et al.* (1987) assessed lineaments, one of which was recognized as a pop-up. Mesoscopic- and macroscopic-scale structures were identified by McFall and Singhroy (1990) using a number of remote sensing techniques.

Investigations of Quaternary sediments near Trenton (Mirynech, 1962) and sources of carbonate building stone in the Kingston-Lake Simcoe region (LeBaron and Williams, 1990), along with measurements of ambient rock stresses and an assessment of pop-ups in the Roblindale Quarry, adjacent to the Salmon River Fault (McKay, 1987; McKay and Williams, 1989), are also relevant to this paper.

GENERAL SETTING AND STRATIGRAPHY

Prince Edward County is located on an irregularly shaped peninsula which extends into the eastern part of Lake Ontario (Fig. 1). The main study area is located in the southern part of the county and encompasses approximately 100 square km bounded by the Lake Ontario shoreline and Latitude 43°56′N, Longitude 77°03′W and Longitude 77°12′W. Because of the low topographic relief, the bedrock is exposed primarily in plan view. Consequently, selected areas outside of the study area, where the strata could be viewed in cross-section, were also examined. These areas include: the Consecon, Mountain View and Picton quarries (Fig. 1) to the west, north and northeast, respectively, and the cliff exposures on the south side of Prince Edward Bay-SouthBay to the east of the study area.

The study area is underlain by upper Middle Ordovician rocks that rest unconformably upon the Precambrian basement rocks of the Grenville Province (Fig. 2), and are overlain by a thin veneer of Quaternary deposits. On a regional scale, the strata are generally undeformed and dip gently toward the south. The total Paleozoic succession in the Belleville area (Fig. 1), 40 km to the north, is 210 m thick (Carson, 1981b), but it is probably somewhat thicker in the study area due to its down-dip location. The Lindsay Formation (Fig. 2) forms much of the bedrock surface and consists of thin- to medium-bedded limestone commonly with irregular shaly partings which impart a nodular texture to the rock. The Verulam Formation, underlying the Lindsay Formation, is composed of interbedded limestones and shale and is exposed at only a few outcrops in the eastern part of the study area.

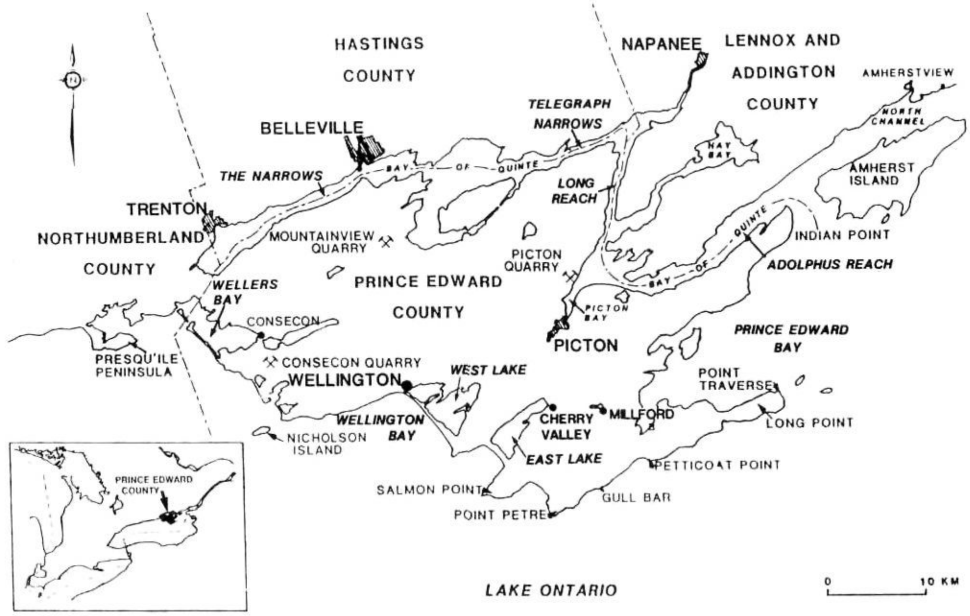

FIGURE 1. Index map of Prince Edward County, southern Ontario.

Carte repère du comté de Prince Edward, au sud de l'Ontario.

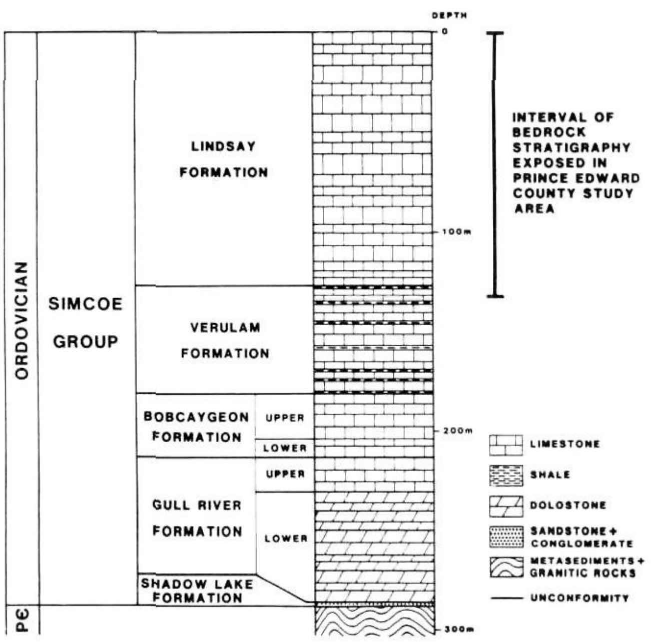

FIGURE 2. Generalized bedrock stratigraphy of Prince Edward County adapted from Williams and Trotter (1984).

Stratigraphie généralisée de la roche en place dans le comté de Prince Edward, adaptée de Williams et Trotter (1984).

MAJOR STRUCTURAL FEATURES AND SEISMICITY

REGIONAL STRUCTURES

Prince Edward County and the surrounding area are cut by a rectilinear system of regional-scale faults which commonly trend 015-020° and 060-070° (McFall *et al.*, in preparation). Three major faults, the Picton Fault and the Salmon River Fault, which trend north-northeast, and the Hamilton-Presqu'ile Fault, which trends east-northeast, transect Prince Edward County and extend southwest into Lake Ontario (McFall and Allam, 1990, 1991; Ontario Geological Survey, 1991a) (Fig. 3). Smaller faults, here named and described below, include the Salmon Point, the Wellington, and the Adolphus faults, all of which trend east-northeast. The Picton, Salmon River, Hamilton-Presqu'ile and Salmon Point fault are probably rooted in the underlying Precambrian basement because each fault coincides with an aeromagnetic lineament (Geological Survey of Canada, 1987a, b; Ontario Geological Survey, 1991b).

The Picton Fault passes through the Town of Picton, where it appears to be a normal fault (Liberty, 1960; Cuddy, 1969) with 30 m of vertical displacement (Liberty, 1960) and crosses the western part of the study area about 1 km north of Point Petre (Fig. 4). It occupies a broad valley which trends approximately 020°, but is infilled with glacio-fluvial sediments that obscure the fault. An attempt was made to determine the amount of displacement across the fault by means of seismic refraction and resistivity surveys conducted across the fault valley. A central zone of water-saturated fractured Paleozoic rock was identified (Allam and McFall, in press), however, the amount of displacement across the fault could not be ascertained due to the paucity of distinct geological or geophysical marker units within the Lindsay Formation and a lack of penetration to the Lindsay/Verulam contact by the seismic signal. In the southern part of Prince Edward County the fault splays into two segments (Carson, 1981b; Williams and Trotter, 1984), one extending south-southwest toward Point Petre (Figs. 1 and 3) and the other extending west-southwest. The latter has been renamed the Salmon Point Fault (McFall and Allam, 1990, 1991).

The Salmon River Fault (Carson, 1981a, b; Liberty, 1963; McFall, 1992) is located north of the study area. It extends southwest, crosses the Bay of Quinte just south of Belleville, and continues across Prince Edward County toward Consecon (McFall and Allam, 1990, 1991; Ontario Geological Survey, 1991a) (Figs. 1 and 3). Carson (1981a, b) indicated

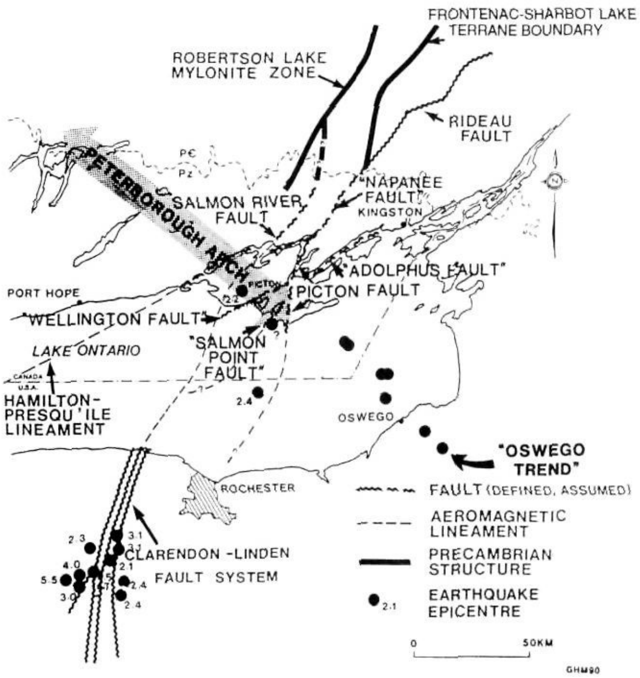

FIGURE 3. Setting of Prince Edward County and eastern Lake Ontario region illustrating the regional shear zones and major faults with seismicity. Numbered data courtesy of the Geological Survey of Canada (1989), unnumbered data from Lamont-Doherty Earth Observatory. Geology from McFall and Allam (1990), LeBaron and Williams (1990) and Ontario Geological Survey (1991).

Carte du comté de Prince Edward et de la région de l'est du lac Ontario montrant les zones cisaillées ainsi que les principales failles et la sismicité. Les données chiffrées sont de la Commission géologique du Canada (1989) et les données non chiffrées sont du Lamont-Doherty Earth Observatory. La géologie provient de McFall et Allam (1990), LeBaron et Williams (1990) et la Commission géologique de l'Ontario (1991).

that it is a normal fault with the northwest side displaced downwards about 30 m relative to the southeast side.

Eighty kilometres southwest of Prince Edward County is the Clarendon-Linden Fault System of western New York State, U.S.A. It is perhaps the longest and oldest seismically active fault in the eastern United States (Fakundiny *et al.*, 1978b) with numerous earthquakes, some in excess of magnitude 5.0, having been reported (Geological Survey of Canada, 1989). Displacement across the fault is 30 m down to the northwest (Chadwick, 1920), which is similar to the displacements on the Salmon River and Picton faults. The Clarendon-Linden Fault is an important element in the structural framework of Prince Edward County because it extends beneath Lake Ontario (Chadwick, 1920; Van Tyne, 1975; Fakundiny *et al.*, 1978a; Hutchinson, 1979) where it continues as the linear, 20 m high bedrock ridge, known as the Scotch Bonnet sill (Thomas *et al.*, 1972; Anderson and Lewis, 1975). It also coincides with a very prominent aeromagnetic lineament, and a series of circular Bouguer gravity highs (Hutchinson *et al.*, 1979). At Consecon, the Clarendon-Linden is collinear with the southern extension of the Salmon River Fault indicating that this fault system continues into southern Ontario through Prince Edward County

The Hamilton-Presqu'ile Fault generally trends 060° and extends east-northeast beneath Lake Ontario from Hamilton to beneath the Bay of Quinte. The dip of the fault is unknown, but across the Bay of Quinte, near Belleville, the formational-contacts are displaced 40 m, down to the north (LeBaron and Williams, 1990). Originally identified by McFall and Allam (1991) as a discontinuous aeromagnetic lineament, its coincidence with the fault along the Bay of Quinte led to its acceptance as a regional-scale fault (Ontario Geological Survey, 1991a; Thurston, 1992).

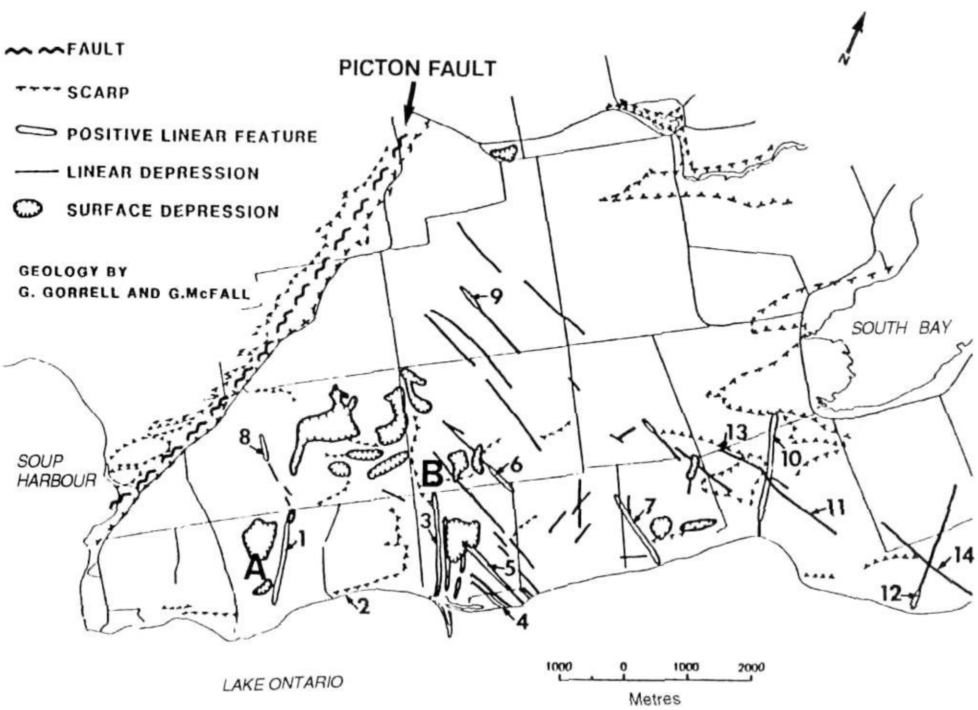

FIGURE 4. Map of study area, Prince Edward County. Numbers correspond to those on Table II; (A) location of a fault dislocating a glaciated bedrock surface; (B) location of open fractures intersecting an abandoned glaciolacustrine beach deposit.

Carte de la région à l'étude dans le comté de Prince Edward. Les chiffres correspondent à ceux du tableau II; (A) emplacement d'une faille ayant disloqué une surface rocheuse au modelé glaciaire; (B) emplacement de fractures ouvertes entrecoupant un dépôt glaciolacustre de plage fossile.

The Salmon Point Fault (McFall and Allam, 1990) trends east-northeast (060°) along the north side of Salmon Point, to the northwest of the study area. Although its presence is supported by stratigraphic offsets (Liberty, 1960), the fault is not exposed. Collinear bathymetric and aeromagnetic anomalies extend the fault farther into Lake Ontario where it may converge with the northern extension of the Clarendon-Linden *Fault System about mid-lake.*

Two additional faults were recently identified by LeBaron and Williams (1990). The Wellington Fault is marked by the prominent bedrock ridge that extends east-northeast from Wellington Bay, along the north shore of West Lake and seems to terminate against, or be offset by, the Picton Fault (Fig. 3). The dip and amount displacement on the fault is unknown. The Adolphus Fault is marked by the topographic expression of the Adolphus Reach segment of the Bay of Quinte. The attitude of the fault is unknown, but the formations are vertically displaced 20 m down on the southeast side. The relationship of the Adolphus Fault to either the Wellington or Hamilton-Presqu'ile faults is unknown.

REGIONAL SEISMICITY

Much of southern Ontario, including Prince Edward County, had been considered to be aseismic (Chapman and Putnam, 1984). Nevertheless, two low-magnitude earthquakes were felt within Prince Edward County in 1987 and 1988 (Fig. 3). The first earthquake, felt only in the Salmon Point area, occurred approximately around Christmas 1987, but was not instrumentally recorded. The second earthquake, located near Consecon, was a magnitude 2.2 event that triggered at 6:22 AM on September 9, 1988 (Geological Survey of Canada, 1989). On March 13, 1979, a magnitude 2.4 earthquake was reported south of Prince Edward County in Lake Ontario, approximately 10 km from the southwestern extension of the Picton Fault. All three recent earthquakes appear to be spatially related to either the Salmon River, Picton or Salmon Point faults (Fig. 3).

On May 1, 1988, five months prior to the magnitude 2.2 event near Consecon, a magnitude 2.1 earthquake occured near Attica on the Clarendon-Linden Fault System (Geological Survey of Canada, 1989). The suspected association of the Salmon River and Salmon Point faults with the seismically active Clarendon-Linden Fault system suggests that these faults may be seismogenic too.

A series of earthquake epicentres defines a linear trend (Oswego trend, Fig. 3) extending from southeast of Oswego, New York, northwest towards Prince Edward County (Barosh, 1986; J.R. Bowlby and A.A. Mohajer, personal communication). This trend coincides with a linear Bouguer gravity anomaly (Ontario Geological Survey, 1991c). Along the southeast projection of this linear trend, near Oswego, New York, Holocene sediments that overlie prominent northwest-oriented fractures and normal faults have been displaced (Young and Putman, 1990). Also, at Nine Mile Point, east of Oswego, movement along a west-northwest to northwest trending, high-angle reverse fault in the Pulaski Sandstone formed a monoclinal warp, with compensatory normal faults, in the overlying Holocene sediments (J.L. Wallach, personal communication). The faults near Oswego may represent part of the structural control of the seismicity, and disruption of the Holocene sediments may be indicative of paleo- or recent seismic activity along the Oswego trend. The Oswego trend and the faults near Oswego lie along the projection of a positive northwest-southeast trending feature in Ontario identified by Liberty (1969), who named it the Peterborough Arch.

MESOSCOPIC STRUCTURES

FAULTS

Few faults have been reported in Prince Edward County because bedrock is commonly masked by Quaternary deposits and, where exposed, is devoid of good marker horizons. Furthermore, known or suspected major fault zones have been eroded and form vegetation-covered valleys. Nevertheless, a detailed examination of the bedrock exposed in quarries and along cliffs within the study area has yielded a number of mesoscopic-scale faults. Faults were discovered in cliff exposures at Point Traverse and along the north shoreline of Long Point (Fig. 1). At Point Traverse three west-northwest trending normal faults, marked by vertical slickensides, displaced shale beds and associated drag folds, were identified. Midway along the north shoreline of Long Point, are two northwest-trending reverse faults with well-developed slickensides and patches of calcite on the fault surfaces. Fault data are summarized in Table I.

Two closely spaced, highly fractured zones that contain abundant veins of calcite were observed cutting the nearly horizontal strata on the north side of Point Traverse (Fig. 1). Many of the fractures within the zones are open, and wave action at the base of the cliff has eroded narrow, elongated caves into the strata along their traces. Dip separations are uncommon but, where present, tend to be less than 5 cm. Well developed, sub-horizontal slickensides are covered by a layer of euhedral calcite crystals which are perpendicular to the fault surfaces and are up to 0.5 cm thick. The layer of euhedral calcite covering the sub-horizontal slickensides indicates *that post strike-slip deformation* was *extensional,* thereby separating the fault surfaces and permitting the

TABLE I

Fault data for Prince Edward County

Location	UTM coordinates	Strike	Dip	Vertical displacement	Slikensides (pitch)	Infilling
A. Normal faults:						
1. Point Traverse Beach	4867250N 350450E	120	80 SW	40 cm	vertical	not apparent
2. East Side Point Traverse	4867450N 354000E	135	85 SW	70 cm	not seen	not apparent
3. North side Point Traverse	4867450N 350000E	125	87 NE	1,25 m	not seen	not apparent
B. Reverse faults:						
4. North side of Long Point	4866800N 347600E	135	17 NE	2,25 m	near vertical (82/053	calcite
5. North side of Long Point	4866800N 347600E	144	19 SW	2 cm	near vertical (86/058)	calcite
C. Strike-slip faults:						
6. North side of Point Traverse	4867400N 349900E	093	87 N	0-5 cm max.	sub-horizontal	calcite
7. Picton Quarry	4879750N 329750E	080	73 S	not known	sub-horizontal	calcite
8. Picton Quarry	4879750N 329750E	058	78 N	up to 20 cm	sub-horizontal	calcite

deposition of calcite. Strike-slip movement was also observed on two faults in the Picton Quarry, which is near the Picton Fault (Fig. 1). One is oriented 080°/73°, is characterized by sub-horizontal slickensides (McFall, 1990) and deforms a Jurassic-aged ultramafic dyke (Barnett *et al.*, 1984) which trends 090°/76°. The second fault trends 058°/78°W, has well developed, sub-horizontal slickensides and a layer of calcite up to 0.4 cm thick on the fault surfaces.

In the western part of the study area (Fig. 4) a glacially polished and striated surface is 30-40 cm lower than the adjacent unpolished, rubbled limestone surface. These two surfaces are separated by an irregular fracture, which trends 125° and contains blebs of weathered calcite (Fig. 5). Arguments postulated for similar relationships between polished and unpolished surfaces (Gorrell, 1988; McFall and Allam, 1990) include lifting of the overriding ice sheet, differential weathering, karst collapse, and post-glacial faulting. Although not impossible, it is unlikely that the ice sheet polished one surface then abruptly rose 40 cm at the exact location of the fracture in order to continue over the higher surface that was subsequently weathered. Differential weathering would more likely result in a weathered surface that was lower than the polished one. Some other mechanism would then be required to change their elevations to the present configuration. Subsurface dissolution of the limestone beds adjacent to the fracture may have been responsible. There is, however, little surface evidence to support this interpretation because the fracture is closed, the edges are angular to sub-angular, and the polished surface and striae are preserved almost right up to the fracture's edge. The simplest explanation for the observed relationships is faulting, which resulted in the downward movement of the polished surface block relative to the unpolished surface block.

FRACTURES

Fractures, spaced about 4 to 8 m apart, are readily observable along the Lake Ontario shoreline, in road-cuts, and in excavations. The fractures are commonly vertical to sub-vertical (dips of 80°-90°) with dominant trends of 015°-035°, 060°-070°, 085°-100° and 120°-130° (McFall and Allam, 1991). Multiplex fractures, described by Fakundiny *et al.* (1978a) as narrow zones of closely spaced, parallel to sub-parallel or crossing curvilinear cracks, were observed at only one location in the study area. Many fractures are open, with gaps ranging from a few millimetres to more than 30 cm, and calcite infilling occurs locally. Common trends of the open and calcite filled fractures are 060°-070° and 120°-130°; calcite is less common in fractures trending 085°-100°. Dissolution has modified the edges of some fractures and the degree of weathering, which is characterized by the amount of smoothing and rounding of the fracture edges and faces, ranges from very little to advanced. On the other hand, the edges and faces of other open fractures are sharp and, by comparison, appear quite fresh.

In areas of little to no soil cover, where water and soil trapped in open fractures provided favourable growing places, fractures are marked by lines of thriving weeds and grasses (Fig. 6). In grass-covered fields where the soil cover is up to 20 cm thick, stripes of greener grass mark the fracture locations. This is particularly marked during dry summer conditions when most of the grass has dried and turned brown. Open fractures display gaps ranging from 10 cm to more than 30 cm in width. Many long, dark, negative-relief lineaments observed on the false-colour infrared aerial photographs proved to be linear surface depressions that are commonly associated with open fractures. These long linear depressions and larger open fractures trend northwest and are most common in the central part of the study area. One well-defined linear surface depression there is related to faulting, and at least two others extend along strike from positive linear features (Fig. 4). Along the shoreline of Long Point, fractures that are open at the top of the 10 to 15 m high cliff exposures generally have gaps of less than 1 cm at water level. In

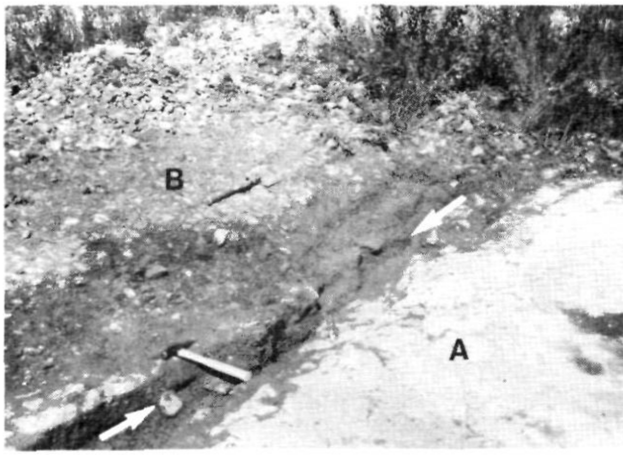

FIGURE 5. A glacially polished and striated block surface (A) abuts an unpolished block surface (B) across an irregular fracture (arrows) (for location see "A" on Fig. 4). This configuration suggests postglacial movement on the fracture.

Surface rocheuse polie et striée (A) adjoignant une surface rocheuse rugueuse (B) en travers d'une fracture irrégulière (flèches) (localisation à la fig. 4). Cette configuration laisse supposer un déplacement postglaciaire sur la fracture.

FIGURE 6. Example of foliage enhanced joints in bulldozed area, Prince Edward County study area.

Fissures exploitées par la végétation dans une zone nivelée par un bulldozer, comté de Prince Edward.

contrast, the strike-slip faults, described above, are open to depths of 10 m below the ground surface.

POP-UPS

Pop-ups are generally elongate surface features which, in cross-section, resemble an inverted "V", although other configurations were documented by Fakundiny *et al.* (1978a). Pop-ups occur throughout southern Ontario (White *et al.*, 1974; White and Russell, 1982) and, in some cases, have developed along fractures or faults (Adams, 1982, 1989). They denote areas of structural instability, and may be indicators of seismically-prone intraplate areas (Wallach *et al.*, 1993). On false-colour infrared aerial photographs of Prince Edward County fourteen long, linear, pale-toned ridges were identified, seven of which were confirmed by direct observation to be pop-ups. Five others are morphologically similar to pop-ups, but have no bedrock exposure, and two were not observable in the field (McFall and Allam, 1990, 1991). The characteristics of the fourteen features are shown in Table II and Figure 4.

TABLE II

Pop-up Information, southern Prince Edward County

Map Number[1]	UTM co-ordinates[2]	Trend	General attributes Length (m)	Height (m max)	Width (m max)
A. Bedrock proven pop-up structures					
1	4858360N 329100E	154°	1130	0.5	6.5
2	4858120N 330200E	096°	200	0.12	1.2
3	4860400N 330170E	155°	1500	1.5	26.0
4	4862340N 332280E	110°	280	0.7	8.3
5	4859400N 331060E	110°	1050	1.8	3.8
6	4860600N 331820E	110°	6000	61	3.6
7	4860690N 334180E	115°	115[3]	0.5	12.4
B. Possible pop-up structures					
8	4859580N 328180E	135°	350	0.4	15.8
9	4862840N 330400E	115°	1500	1.2	8.0
10	4862340N 335580E	165°	1700	0.6	20.0
11	4862480N 335280E	095°	900	0.6	16.0
12	4861840N 338500E	175°	900	0.3	12.4
C. Other bedrock structures (possibly eroded pop-ups)					
13	4862160N 336120E	100°	750	0.9	20.6
14	4862200N 338280E	105°	1400	0.5	6.0

1. See Figure 4
2. UTM co-ordinate of approximative centre of structure
3. Onshore segment

All of the pop-ups trend northwest-southeast (110°-158°) and are located east of the Picton Fault (Fig. 4). In open fields, pop-ups are long grassy ridges, up to 2 m high (Fig. 7), with the land surface on opposite limbs commonly appearing at different elevations. One pop-up, exposed on the Lake Ontario shoreline, has flanks dipping in opposite directions away from an axial zone which is filled with fault gouge (Fig. 8). At least three pop-ups formed in association with faults. Other features associated with the pop-ups include: a) en-echelon fractures along the axes, b) generally sub-angular to sub-rounded axial fracture edges, c) the common occurrence of calcite, or rarely barite, veins in the bedrock immediately adjacent to, or cutting, the axial zone, and d) lack of polish or striations on the upper surface of the limbs.

DISCUSSION

Mesoscopic-scale, northwest-trending (120°-135°) normal and (135°-144°) reverse faults, along with east-northeast to east-west oriented (058°-090°), sinistral strike-slip faults cut the upper Middle Ordovician rocks in Prince Edward County. The normal faults formed in response to a stress field with the greatest principal stress, σ_1, either vertical, or horizontal and oriented approximately northwest. The other two fault types, however, would have developed as a consequence of a compressional stress field in which σ_1 was oriented generally northeast, as it is at the present time in eastern North America (Zoback and Zoback, 1980; Yang and Aggarwal, 1981; Adams and Basham, 1987). This implies at least two periods of Paleozoic, or younger, faulting, although the exact ages of neither can be established due to the absence of post upper

FIGURE 7. Largest pop-up appears as a 1.8 m high, grass covered ridge that transects the surrounding fields of the study area (see #5 on Fig. 4 for location).

La plus importante structure de soulèvement est une crête de 1,8 m de haut qui traverse les champs environnants (emplacement du n° 5 à la fig. 4).

FIGURE 8. Bedrock exposure of pop-up on shoreline of the study area (see #4 on Fig. 4 for location). Note the limbs of the pop-up dipping away (arrows) from the axial zone (A).

Affleurement dans une structure de soulèvement sur le rivage (emplacement du n° 4 à la fig. 4). Noter les flancs de la structure de soulèvement s'inclinant vers l'extérieur.

Middle Ordovician rocks. The normal faults in Prince Edward County parallel those of the Ottawa-Bonnechere Graben, which have been interpreted as resulting from the failed rifting of the continent during the early Mesozoic (Kumarapeli and Saull, 1966). This suggests that an early Mesozoic age for the normal faults of Prince Edward County is reasonable, though an older age cannot be ruled out.

The compatibility of the northwest-trending reverse faults and east-northeast to east-west, sinistral strike-slip faults suggests a common formational age for the two, as well as for other cogenetic structures such as northwest-oriented folds. However, it is naive to take the notion of common age too literally because, under any stress system, not all genetically-related structures would form, or be reactivated, at precisely the same time. Direct evidence of age relationships were not seen in Prince Edward County, but just to the northeast, about 8 km west of Napanee (Fig. 1), intersecting mesoscopic-scale structures coexist. There a northwest-trending (130°) curvilinear anticline is cut by a left-lateral strike-slip fault, trending 080°. The slickensides on the fault surface maintain a uniform, nearly sub-horizontal plunge, irrespective of whether the fault crosses the hinge or either of the oppositely-dipping limbs. Thus, at that location, the east-west strike-slip fault post-dates the fold. A Jurassic-aged dike (Barnett *et al.*, 1984) in the Picton Quarry has been deformed by an east-west oriented strike-slip fault, thereby demonstrating that least some east-west strike-slip faults are Jurassic or younger in age. However, the sense of movement along that fault in the Picton Quarry could not be determined.

On a regional scale, the eastern Lake Ontario region is dominated by major, generally northeast-trending faults (Fig. 3). The Picton, Salmon River and, seismically active, Clarendon-Linden faults are collinear with aeromagnetic lineaments and are interpreted as being part of the same major fault system that crosses Lake Ontario from New York State into Prince Edward County. To the northeast, the projection of the Picton Fault coincides with the Frontenac-Sharbot Lake Terrane Boundary and the Rideau Fault in the exposed Precambrian rocks (Ontario Geological Survey, 1991a). These characteristics strongly suggest that the fault system which crosses Lake Ontario is a major Precambrian shear zone which has experienced post-Middle Ordovician reactivation.

The Hamilton-Presqu'ile and the Salmon Point faults cut the underlying Precambrian Grenvillian rocks and have linear aeromagnetic signatures which cut across the predominant NE-trending grain of the Grenvillian terranes. The Hamilton-Presqu'ile and the Salmon Point, along with the Wellington and Adolphus, constitute a suite of east-northeast trending faults. The ages of those faults are unknown, however they displace upper Middle Ordovician strata indicating that they have been active since the upper Middle Ordovician.

Pop-ups generally are considered to be post-glacial in age (Hofmann, 1966; Simmons, 1966; White *et al.*, 1974; White and Russell, 1982; Williams *et al.*, 1985; Adams,1989). In Prince Edward County, however, it is impossible to verify that all of the pop-ups formed subsequent to glaciation. Normally, the age of a structure can be obtained by analyzing datable material associated with it, but such material is rare for bedrock structures in Prince Edward County. In order to confirm a post-glacial age in the absence of datable material, either glacially polished or striated surfaces must be displaced, or layered glacial or post-glacial sediments that are deformed, but do not thin, must be present over the structure. For the Prince Edward County pop-ups, neither polished nor striated surfaces were observed on the exposed limbs of the pop-ups, and sediment cover on the pop-ups is generally thin to absent.

It would seem unlikely that pop-ups that protrude above the land surface would survive glaciation, however, high fluid pressures could be generated at the base of a glacier that would permit the ice, and its tools, to pass over the pre-existing pop-up without eroding it. Nevertheless, as pointed out by Wallach *et al.* (1993), the degree to which the fracture-bedding intersection is weathered along the axes of pop-ups may be diagnostic, particularly in limestone terranes where the bedrock is quite soluble. The relatively sharp, sub-angular edges of fractures along the axes of the pop-ups implies that the pop-ups in Prince Edward County formed under low confining pressure in fairly recent times. Furthermore all of the pop-ups documented in this study are orthogonal to the current ambient principal horizontal compressive stress (σ_1), strongly suggesting a cause and effect relationship between the two. Combining all of the foregoing characteristics, it is very likely that the pop-ups in Prince Edward County formed following retreat of the last glacial phase which, according to the definition given in the introduction of this paper, means that they are truly neotectonic structures.

Besides the pop-ups, another likely neotectonic indicator is the fracture, against which a glacially polished and striated surface is in contact with an unpolished, rubbly surface, with the latter about 30 to 40 cm higher than the former (Fig. 5). If this juxtaposition is due to faulting, as suspected, the character of the adjacent surfaces means that the faulting occurred following the last glaciation.

The fault system comprising the approximately northeast-oriented Clarendon-Linden, Picton and Salmon River faults is intersected by the east-northeast trending Hamilton-Presqu'ile, Salmon Point, Wellington and Adolphus faults. Too, the Peterborough Arch (Liberty, 1969) and the Oswego trend of earthquakes, which lies along the projection of the Peterborough Arch, suggest that a major northwest-oriented structural element may also cut through Prince Edward County. If so, this feature would intersect the aforementioned faults. According to Hildenbrand (1985) and Barosh (1986) seismicity in parts of east-central North America appears to be controlled by the intersection of major structural features, particularly where northwest and northeast-trending structures intersect. The possible existence of this situation in the area of Prince Edward County suggests that, although no macroscopic seismic event is known in or near Prince Edward County, the area may be subject to a greater seismic hazard than heretofore perceived.

SUMMARY AND CONCLUSION

Prince Edward County has classically been considered to be a seismically quiescent part of the stable North American craton, implying that little or no deformation has occurred in the past and, therefore, little or none is expected in the future. However, mesoscopic-scale bedrock structures, such as fractures, pop-ups and faults in Prince Edward County indicate there has been more than one period of tectonic instability during the Phanerozoic; the characteristics of the pop-ups suggest that they formed since retreat of the last glaciation about 12,000 years ago. Seismicity (some in excess of magnitude 5) along, or adjacent to, the Clarendon-Linden Fault System which, by extension, appears to include the Salmon River and Picton faults implies that the latter faults, which cut through Prince Edward County, may be tectonically active. Clearly there is a need to revise the perception of the long-term structural stability and the potential for the occurrence of major seismic events within, and adjacent to, Prince Edward County.

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