GEOLOGIC RECORD OF INTRAPLATE SEISMICITY IN SOUTHERN ONTARIO

by

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This thesis contributes to an understanding of intracratonic seismicity in eastern North America by presenting geological evidence for past earthquake activity within disturbed rocks and sediments (‘seismites’) in Southern Ontario. A major impediment to understanding modern day earthquake risk is the limited historic record of earthquake activity (early seventeenth century) and an instrumental record of short duration (typically <75 years). Current consensus, based on the instrumental record, is that seismicity is the product of brittle failure of upper crust and that pre-existing Precambrian structures are being reactivated as the North American plate moves westward. Surprisingly little attention has been paid to testing the reactivation hypothesis by systematic examination of the geologic record which is the central objective of this thesis. Study of Late Ordovician to mid-Silurian strata of the Michigan and Appalachian basins exposed in quarries in the Bruce Peninsula, outcrops along the Niagara Escarpment and in drill core identifies unusual geographically widespread horizons of pillowed, faulted and resedimented facies within otherwise undisturbed strata which are interpreted as seismites.

The younger sedimentary record consists of unconsolidated glacial (>13,000 years), lateglacial (c. 13-10,000 years) and postglacial (< 10,000 years) sediments. Interpretation of glacial sediments is complicated by widespread glacio-tectonism but a wealth of high
resolution geophysical data collected from 16 lakes demonstrates that lateglacial and postglacial sediments in lake basins are ‘natural seismographs’ that record ancient earthquakes. Lateglacial and postglacial neotectonic activity is recorded by faults, slumps and debris flows on many lake floors located above prominent Precambrian terrane boundaries and rifts, especially within lakes Timiskaming and Kipawa, recording ongoing deformation within the Western Quebec Seismic Zone (WQSZ) along the Ottawa-Timiskaming Graben. Exceptionally thick mass flow successions in Lake Timiskaming along the floor of the Ottawa-Timiskaming Graben point to a higher frequency of earthquakes and slope failure during deglaciation and rapid glacio-isostatic rebound though faulting demonstrably continues into the postglacial.

Data presented in this thesis support the model that ongoing mid-plate earthquake activity is a consequence of brittle deformation of the upper crust of the North American plate concluding that basement structures influenced Paleozoic sedimentation in the Michigan and Appalachian basins.
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STATEMENT OF RESEARCH CONTRIBUTIONS

Chapter 2 – Seismites within Silurian dolostone laminites of the Bruce Peninsula, Ontario, Canada triggered by reactivation of the Grenville Front Tectonic Zone.

All field work including measurements, logging of outcrop and core, collection of samples, and photography was conducted by K. Wallace with assistance of student field staff. Logistical support and direction was provided by Dr. N. Eyles. Rock samples were provided by the Big Island Quarry and rock blocks cut by Terraprobe Inc. Thin sections were prepared by the Thin Section/Rock Cutting Lab at Queen’s University, Department of Geological Science and Engineering in Kingston, Ontario. Photography and measurement of thin sections was conducted by HD Analytics in London, Ontario. Counting and interpretation of laminations was conducted by K. Wallace. Assistance with statistical analysis of laminites was provided by K. Kennedy and G. Arhonditsis. Preparation of figures was by K. Wallace with assistance of M. Doughty. Manuscript was prepared by K. Wallace and Dr. N. Eyles.

Chapter 3 – Seismites within Ordovician-Silurian siliciclastic and carbonate shoreface strata of Southern Ontario, Canada.

For this chapter, all field work including measurement of strata, collection of samples, photography and measurements was conducted by K. Wallace with assistance of student field staff. Logistical support and direction was provided by Dr. N. Eyles. Figures were prepared by K. Wallace with assistance of M. Doughty. Manuscript preparation was by K. Wallace and Dr. N. Eyles.

Chapter 4 – Lake Sediments as natural seismographs: earthquake-related deformations (seismites) in central Canadian lakes.

Data collection in the field (seismic subbottom, sidescan and magnetometer data) was accomplished by M. Doughty, Dr. N. Eyles and Dr. J. Boyce. Dr. N. Eyles was responsible for logistics and navigation; with additional field assistance for data collected at Lake Timiskaming, Lake Simcoe, Lake of Bays, Lake Joseph, Lake Muskoka and Lake Rousseau. Compilation and mapping of basement structures, terranes, lineaments, and Paleozoic faulting was completed by K. Wallace. Literature review and summaries of lake bottom survey research, basement geology, Paleozoic faulting, historical seismicity, paleoseismic features of Ontario and field work at Lake Timiskaming area was completed by K. Wallace. Manuscript preparation was by M. Doughty, Dr. N. Eyles, K. Wallace and Dr. C. Eyles.

Chapter 5 – Summary and Conclusions

Compilation and mapping of seismites and significant geologic structures completed by K. Wallace with drafting assistance of M. Doughty.
CHAPTER 1:
INTRODUCTION

1.1 STUDY RATIONALE

Until quite recently, the Canadian Shield and offlapping Paleozoic platforms in mid-continent North America were regarded as having been tectonically stable for many millions of years and thus of low seismic risk. This is no longer considered realistic. Mohajer (1997) estimated a major (M7) earthquake can be considered ‘credible’ in the heavily populated southern Ontario-Quebec corridor; a recent report for the Insurance Bureau of Canada by AIR Worldwide (2013) concluded that the risk of such an earthquake is 1:500 and is estimated to create $61 billion of damage to infrastructure of which only $12 billion is currently insured. Expected ground motions are modelled to exceed the design limits for nuclear generating facilities at Pickering and Darlington along the northern shore of Lake Ontario near Toronto. As seismic networks have expanded there is growing recognition of widespread frequent intraplate seismic activity in central Canada which experiences hundreds of intraplate earthquakes each year (Fig. 1.1; Adams and Basham, 1989; Wallach et al., 1998; Tremblay et al., 2003; Kim et al., 2006; Dineva et al., 2004, 2007; Mereu et al., 2013; Natural Resources Canada, 2014) that threatens infrastructure both onshore and also offshore along the eastern Canadian continental margin (Stein and Mazzotti, 2007). AIR Worldwide (2013) also identified that current Canadian seismic risk maps on which building codes are based are outdated.

Recent large earthquakes in Canada include the Timiskaming Earthquake of 1935 (M6.2) which was felt over an area of 2.5 million km² and the 1944 (M.5.8) Cornwall
Earthquake which to date is Canada’s costliest in terms of damage to infrastructure (approximately $2 million – 1944 dollars; Bent, 1996; Fig. 1.2).

Against a backdrop of increased risk as urban populations expand, the origin of mid-plate seismicity appears to be related to the reactivation of Precambrian structures often deeply buried below Phanerozoic strata. These structures record major phases of plate tectonic activity involving episodes of crustal accretion and rifting along the eastern North American continental margin over the last billion years (Fig. 1.3; Eyles et al., 1993; Boyce and Morris, 2002; Tremblay et al., 2003; Bartholomew and Van Arsdale, 2012; Cox et al., 2012). Of particular concern in eastern central North America is the Western Quebec Seismic Zone (Forsyth, 1981) a belt of enhanced seismic activity that extends from Canada into the coterminous US and poses a regional risk to mines, critical nuclear facilities and the large urban areas of New York, Montreal and Ottawa (Fig. 1.4). In the case of the nation’s capital and Montreal, seismic risk is compounded by the presence of soft glaciomarine sediments (Leda Clays) and aged infrastructure (Motazedian and Hunter, 2008; Rosset and Chouinard, 2008). The recent Val-des-Bois Earthquake (M.5.0) of 2010 caused the strongest shaking ever measured in the city of Ottawa (Fig. 1.2; Natural Resources Canada, 2013).

There are many practical difficulties in fully understanding mid-plate seismicity (Bartholomew and Van Arsdale, 2012). The major challenge is that Precambrian structures are not exposed at surface in the vicinity of the major urban areas but are hidden below thick covers of Paleozoic strata and Pleistocene glacial sediments (Fig. 1.5). The historic record of earthquake activity only began relatively recently in the early seventeenth century and the instrumental record is also of very short duration (<75 years; Stevens, 1980; Basham et al., 1982; Lamontagne et al., 2008). The lack of a detailed network of recording instruments
across such a large region is another problem (Mazzotti, 2007). An area of discussion and contention revolves around whether mid-plate seismicity in the glaciated portion of North America is primarily related to continuing glacio-isostatic rebound and thus can be expected to decrease in the future, or reflects persistent ongoing movement of the North American plate (Ma et al., 2008) or both. A similar discussion is occurring in northwest Europe (Mörner, 2011). Discrimination of glaciotectonic deformation structures caused by a variety of ice-contact processes from non-glacial neotectonic structures is also much debated (see below).

Adams (1992) is a significant publication because it includes a first detailed assessment by the Ontario Geological Survey (Milne, 1992) of known faults in Southern Ontario and their geologic history and possible relationship to seismic activity. Much discussion in that document focussed on what faults were considered sufficiently significant to portray on new regional map compilations of Southern Ontario. The database was necessarily limited by a lack of data on modern seismicity but was further constrained by a prevailing attitude that assessment of seismic risk in the heavily populated Southern Ontario region was somehow a ‘federal responsibility’ (Milne, 1992). The discovery of prominent faults in Pleistocene sediments exposed in the Rouge Valley within 7 km of the Pickering Nuclear Generating Facility (PNGF) generated much debate as to how to discriminate neotectonic faults from those of glaciotectonic origin (Godin et al., 2002, 2003; Eyles and Mohajer, 2003) and to which to this day has not been satisfactorily resolved. Despite this, in the light of renewed public concern after the March 2011 Japan Earthquake, the Director of the Pickering Nuclear Generating Facility (PNGF) stated that ‘there are no known active faults’ in the vicinity of the facility (Ontario Power Generation, 2011). This statement,
intended presumably to allay public concern about the Rouge Valley faults, is misleading as it ignores uncertainty as to the origin of those structures and disregards the presence of a major seismogenic terrane boundary under the facility (the Central Metasedimentary Belt Boundary Zone).

Wallach et al. (1998) was the first major attempt to relate modern seismicity to Precambrian source areas in Southern Ontario and they identified the importance of major terrane boundaries such as the Central Metasedimentary Belt Boundary Zone that cross the GTA at depth (Fig. 1.5; see also Dineva et al., 2004, 2007). Other investigations identified the regional state of stress and its relationship to joint patterns, the focus here being rock mass stability and geomechanics in regard to deep storage of nuclear waste (NWMO and AECOM, 2011). Some workers noted a distinct joint control on modern drainage systems and shoreline orientations (Eyles and Scheidegger, 1995; Eyles et al., 1997) while the trend of buried valleys cut into bedrock below Pleistocene sediments was related to Precambrian structures below the Paleozoic cover indicating reactivation. There has also been considerable interest in joints in glacial sediments such as tills and glaciolacustrine clays in regard to the search for appropriate long term landfill sites and their ability to contain leachate (Grisak and Cherry, 1975; D’Astous et al., 1989; Rowe and Booker, 1990; Boyce et al., 1995). Zones of pop-ups (stress-release features) affecting shales outcropping on the floor of western Lake Ontario adjacent to Toronto were mapped by Thomas et al. (1993) and linked to several prominent geophysical lineaments in the Precambrian. Geomorphic evidence of large (M>7) earthquakes at 7060 years before present (ybp) and 4550 ybp occurs as relict landslides in lateglacial glaciomarine Leda Clays within the Ottawa Valley (Aylesworth et al., 2000; Aylesworth, 2007). Lake sediments constitute what has been called
‘natural seismographs’ (e.g., Moernaut et al., 2009; Strasser et al., 2013) and Shilts (1984) pioneered examination of the sedimentary record of late and postglacial seismic activity focusing on the sub-bottom stratigraphy and bottom morphology of postglacial lakes but such work was discontinued at the end of that decade (see Shilts and Clague, 1992).

1.2 OBJECTIVES OF THIS THESIS

The research being described below grew out of the need to better understand the geologic record of earthquake activity in the heavily populated Southern Ontario region by conducting a systematic survey of Paleozoic and postglacial sediments. The underlying assumption is that such strata are natural seismographs and may record ancient earthquake activity. Surprisingly, in view of very serious concerns regarding the magnitude of risk to modern infrastructure posed by intraplate earthquakes, such a survey has never been undertaken. Several authors have described structures they suggest might be “possible” seismites within Paleozoic strata (see Table 1.1 for summation of existing literature) however until now no comprehensive systematic study has been undertaken. Table 1.1 presents a comprehensive summary of literature referencing seismic or tectonic deformation structures within Paleozoic, lateglacial, and postglacial sediments.

The current consensus is that intraplate seismicity is the product of brittle failure of the upper crust and that pre-existing Precambrian structures are being reactivated as the North American plate moves westward with eastern North America under a predominately ENE compressive stress regime (Fig. 1.3; Zoback and Zoback, 2007; Mazotti and Townend, 2010). There has however been a lack of attention to examining the geologic record to test
this hypothesis. The record of paleo-earthquakes within the rocks and sediments of Southern
Ontario may be related to reactivation of major crustal structures. The primary objective of
this thesis is to systematically assess the geologic record of paleoseismicity in Southern
Ontario to test the reactivation hypothesis. The present thesis diverges from past practice by
presenting the results of a systematic examination of the Paleozoic sedimentary cover that
rests on the Precambrian; the rationale being that such strata might contain seismites, and in
turn, further identifies Precambrian structures that, by comparison with the record preserved
in postglacial lakes, have had a recurring history of activity.

Assessment of the significance of the Paleozoic and postglacial record of earthquake
activity in central Canada in terms of identifying the importance or otherwise of specific
Precambrian structures is in no small measure dependent on an up-to-date mapping of
instrumentally-recorded earthquake epicentres. Comparison between the different data sets
provides a meaningful method to test the hypothesis of structural control on seismicity and
allows identification of persistent structures. Thus a major first step was compilation of
earthquake epicentres and review of their relationship with known structures.

Chapters 2 and 3 of this thesis greatly expand the known geologic record of past
earthquake activity by describing and interpreting deformation structures within Paleozoic
(Ordovician-Silurian-Devonian) sedimentary strata of Southern Ontario that are confidently
interpreted as having been produced by co-seismic ground shaking of unconsolidated sea
floor sediments. Such seismites are described from lengthy natural outcrops principally along
the Niagara Escarpment and Gorge, in large quarries on the Bruce Peninsula and from drill
core (Figs. 1.5 and 1.6).
Chapter 2 describes extensive outcrops of unusual mid-Silurian rhythmically-laminated dolostones which display syndepositional thrust faults associated with two intraformational horizons of clast breccia and folding bedding. These structures suggest resedimentation and mass flow events on the then sea floor associated with tectonic compression in an otherwise passive tectonic intracratonic setting. The clear geographic relationship between seismites and Precambrian structures below confirm similar work in the adjacent US in Michigan and Ohio suggesting these structures were active at a time of know rapid subsidence of the Michigan Basin pointing to reactivation of the Grenville Front Tectonic Zone (Figs. 1.6 and 1.7).

A systematic survey of Lower Paleozoic shoreface sandstones and shale (Ordovician-Silurian) in outcrop and drill core evaluating the sedimentary record of paleo-seismicity during subsidence of the Appalachian Basin is presented in Chapter 3 (Figs. 1.6 and 1.7). Laterally-extensive beds of large synsedimentary Lower Silurian ball-and-pillow structures within the Thorold Formation, along with seismites displayed within other Lower Paleozoic strata, suggest that western Lake Ontario and the Niagara Peninsula region experienced recurrent seismicity from the Upper Ordovician through mid-Silurian. Seismicity is likely related to reactivation of complex basement structures and poorly understood geophysical lineaments that are active in the present day.

Chapter 4 of this thesis extends the known database of glacial and postglacial subaqueous deformation structures by describing deformation structures from sixteen lakes in Ontario and adjacent parts of Quebec; the largest such compilation to date (Fig. 1.6). In the absence of post-Devonian strata in Southern Ontario the subsequent rock record of earthquake activity is necessarily incomplete until geologically recent time. The younger
sedimentary record consists of unconsolidated glacial (>13,000 years), lateglacial (c. 13-10,000 years) and postglacial (< 10,000 years) sediments. Interpretation of glacial sediments is complicated by widespread glacio-tectonism but a wealth of high resolution geophysical data (sub-bottom reflection, side scan and multibeam data) collected from sixteen lakes (Gull, Muskoka, Joseph, Rousseau, Ontario, Wanapitei, Fairbanks, Vermilion, Nipissing, Lake Huron, Georgian Bay, Mazinaw, Simcoe, Timiskaming, Kipawa, Parry Sound and Lake of Bays) demonstrates that fine-grained late glacial and postglacial sediments in lake basins are ‘natural seismographs’ that record ancient earthquakes (Fig. 1.6). Significantly, many lakes fill bedrock basins structurally-controlled by Precambrian basement structures (shear zones, terrane boundaries and other geophysical lineaments; Fig. 1.5). Sediment faulting, diapiric deformation and slumping of lakefloor sediments located over basement structures suggest both lateglacial seismic influence and, in the case of lakes Timiskaming and Kipawa, neotectonic deformation of postglacial sediments. Exceptionally thick mass flow successions in Lake Timiskaming located along the floor of the Ottawa-Timiskaming Graben suggest a higher frequency of earthquakes and slope failure during deglaciation and rapid glacio-isostatic rebound, but faulting and failure of lakefloor sediments is ongoing confirming the hypothesis that the graben is a weak zone within the North American plate.

1.3 STRUCTURE OF THIS THESIS

This thesis consists of 3 chapters (Chapters 2 to 4) formatted for publication in scientific journals. Each of the chapters contributes to the principal objectives of the thesis described above. The content of this thesis is summarized below:
Chapter 2 – Seismites within Silurian dolostone laminites of the Bruce Peninsula, Ontario, Canada triggered by reactivation of the Grenville Front Tectonic Zone.

The content of this chapter, along with Chapter 3, has been submitted as one comprehensive paper entitled Seismites within Ordovician-Silurian carbonates and clastics of Southern Ontario, Canada and implications for intraplate seismicity to Sedimentary Geology (Vol. 316 [2015] p. 80-95). Chapter 2 evaluates unusual rhythmically-laminated dolostone displaying syndepositional thrust faults associated within two unusual intraformational horizons of clast breccia and folded bedding. Assessed in both outcrop and drill core across the central Bruce Peninsula, the structures are confirmed as seismites generated by an earthquake of at least M7. The geographically extensive seismites lie less than 50 km from the Grenville Front Tectonic Zone suggesting reactivation of the structure at a time of enhanced subsidence of the Michigan Basin.

Chapter 3 – Seismites within Ordovician-Silurian siliciclastic and carbonate shoreface strata of Southern Ontario, Canada.

The content of this chapter, along with Chapter 2, has been submitted as one comprehensive paper entitled Seismites within Ordovician-Silurian carbonates and clastics of Southern Ontario, Canada and implications for intraplate seismicity to Sedimentary Geology (Vol. 316 [2015] p. 80-95). Deformation structures within Upper Ordovician through mid-Silurian strata observed in outcrop and drill core along the Niagara Escarpment, Peninsula and Gorge were systematically evaluated for a seismic origin. This work confirms that geographically extensive seismites across the region were generated by earthquakes of M5 through M8 suggesting that the western Lake Ontario and Niagara Peninsula region experienced recurrent seismicity from the Upper Ordovician through mid- Silurian. Seismicity was likely related to
complex basement structures and poorly understood geophysical lineaments in the complexly structured region.

Chapter 4 – Lake Sediments as natural seismographs: earthquake-related deformations (seismites) in central Canadian lakes.

This chapter was presented by K. Wallace (presenting author) at the Seismological Society of America Annual Meeting, May 2, 2014 in Anchorage, Alaska under the title: Paleoseismic evidence for persistent intraplate seismicity associated with reactivation of Precambrian crustal structures in central Canada. The chapter (Sedimentary Geology 313, 45-67) summarizes more than 2,000 km of track line sub-bottom acoustic profiling surveys of sixteen lake basins of central Canada. Results show that a number of lakes exhibit lateglacial deformation related to isostatic rebound immediately following deglaciation. Lake Kipawa shows evidence of slumping related to the 1935 M 6.2 Timiskaming earthquake. Lake Timiskaming exhibits extensive faulting, deformation structures, and large slumping related to lateglacial and postglacial seismic activity. The proximity of these lakes to significant crustal structures and terrane boundaries suggests a relationship to the reactivation of buried crustal structures and seismic activity supporting the model that ongoing mid-plate earthquake activity is a result of brittle deformation of the upper crust of the North American plate.

Chapter 5 – Summary and Conclusions

Chapter 5 summarizes the results and conclusions of the individual papers presented in this thesis. A discussion of the overall contribution of this thesis to furthering understanding of the geologic record of paleoseismicity in Southern Ontario is provided. Recommended
directions for further research are discussed.
Table 1.1: Published evidence of earthquakes in the geologic record of Southern Ontario.

<table>
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<tr>
<th>Ref. #</th>
<th>Age</th>
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## Table 1.1 (cont’d): Published evidence of earthquakes in the geologic record of Southern Ontario.

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Table 1.1 (cont’d): Published evidence of earthquakes in the geologic record of Southern Ontario.

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Figure 1.1  Earthquake epicentres in eastern Canada over a 12 month period from September 7, 2013 to September 8, 2014 (after Natural Resources Canada, 2014).
Figure 1.2  Focal mechanisms of major earthquakes for Southern Ontario and surrounding areas since 1935 including seismicity (1980-2005). Year of earthquake outlined in red. After Dineva et al. (2007) and references therein. Focal mechanism for Val des Bois earthquake after United States Geologic Survey (2010).
Figure 1.3  Broad scale structure of eastern North America resulting from formation and breakup of Rodinia and Pangea with historic earthquake epicentres (1627 to 2013 AD) after Natural Resources Canada (2013) and Halchuk (2009). Major structural boundary locations were adapted from Bartholomew and Van Arsdale (2012), Boyce and Morris (2002), Carr et al. (2000), Mazzotti (2007), Thomas (2006) and Withjack et al. (2002). Direction of maximum regional compressive stress (for the study area) derived from Nuclear Waste Management Organization and AECOM Canada Ltd. (2011).
**Figure 1.4**  Earthquake epicentres in eastern North America (1627 to 2013 AD) and regional structural elements including the St. Lawrence Rift system and associated grabens (epicentres from Natural Resources Canada, 2013 and Halchuk, 2009). The Western Quebec Seismic Zone (Forsyth, 1981; WQSZ) is indicated.
Figure 1.5  Generalized subsurface geology of Southern Ontario from London to Kingston, Ontario. Relative stratigraphic level of strata described in this thesis are indicated with Chapter references (after Eyles, 2002). CMBBZ is the Central Metasedimentary Belt Boundary Zone.
Figure 1.6  Study area locations. Structural data summarized from Bartholomew and Van Arsdale (2012), Boyce and Morris (2002), Carr et al. (2000) and Mazzotti (2007). GFTZ: Grenville Front Tectonic Zone; CMBBZ: Central Metasedimentary Belt Boundary Zone; NPLZ: Niagara-Pickering Linear Zone; HLEL: Hamilton-Lake Erie Lineament; HPL: Hamilton-Presqu’ile Lineament; GBLZ: Georgian Bay Linear Zone.
Figure 1.7  Major tectonic elements and structures of Southern Ontario. CMBBZ – Central Metasedimentary Belt Boundary Zone. GFTZ-Grenville Front Tectonic Zone; CMBBZ-Central Metasedimentary Belt Boundary Zone. Hashed rectangle indicates study area (after Armstrong and Carter, 2010 and Boyce and Morris, 2002 and references therein).
REFERENCES


CHAPTER 2:

SEISMITES WITHIN SILURIAN DOLOSTONE LAMINITES OF THE BRUCE PENINSULA, ONTARIO, CANADA, TRIGGERED BY REACTIVATION OF THE GRENVILLE FRONT TECTONIC ZONE

ABSTRACT

The mid-Silurian (c. 428 Ma) Eramosa Member of the Guelph Formation in the Wiarton area of the Bruce Peninsula in Ontario, Canada consists of flat-lying, rhythmically-laminated bituminous dolostones. These record a hypersaline quiet water backreef lagoonal environment along the shallow water margins of the intracratonic Michigan Basin. Outcrops in several quarries display syndepositional thrust faults associated with two unusual intraformational horizons of clast breccia and folded bedding. They indicate unusual resedimentation and mass flow events associated with tectonic compression in an otherwise passive intracratonic setting. Deformation structures are well exposed on extensive rock faces in one large quarry (Big Island Quarry) with stratigraphically correlative structures present in quarries 2.5 km to the south and in drill core from sites 15 km distant indicating widespread extent of correlative deformation horizons. These are attributed to repeated earthquakes when sediments were subject to compressional stresses and faulting and near-surface sea floor sediment was brecciated and re-mobilized as debris flows. These structures and associated resedimented facies are confidently identified as seismites. Seismites are abruptly overlain by a mottled homogenized unit recording extensive bioturbation of laminites and rapid environmental change immediately following deformation. Earthquake activity likely reconfigured the local mid-Silurian coastal morphology as a consequence of co-seismic
subsidence of the Michigan Basin allowing the ingress of relatively low salinity seawater and an influx of organisms resulting in extensive bioturbation.

Deformation structures (seismites) occur close (<50 km) to a major crustal boundary (Grenville Front Tectonic Zone: GFTZ) present in the Precambrian basement underlying Paleozoic carbonates. This structure has a long Phanerozoic history of reactivation which continues to the present day. Data presented here indicates that the GFTZ was seismically-active during the mid-Silurian and that deformation structures record an earthquake of at least M7; broadly correlative mid-Silurian seismites also attributed to reactivation of the GFTZ occur in adjacent parts of the Michigan Basin in the US some 500 km distant. Seismic activity occurred during a time of greatly enhanced subsidence of the Michigan Basin and likely involved reactivation of the underlying Precambrian basement.
2.1 INTRODUCTION

Intraplate earthquakes in mid-continent North America are a cause for international concern in Canada and the USA because they threaten infrastructure in several heavily populated areas. However, their frequency and origin(s) are still not well understood but thought to arise from reactivation of deeply-buried basement structures in response to modern stress fields arising from migration of the North American plate (Adams and Basham, 1989; Ebel and Tuttle, 2002; Dineva et al., 2004; Mazzotti and Adams, 2005; Doughty et al., 2013). It is significant that Canada’s most damaging earthquake to date occurred not in British Columbia along the active North American plate margin but at Cornwall in Eastern Ontario in 1944 (Cassidy et al., 2010). This was the consequence of reactivation of the extensional St. Lawrence Rift System (SLRS) formed during Pangean breakup after 200 Ma (Mazzotti et al., 2005; Cassidy et al., 2010). SLRS underlies the cities of Montreal and Ottawa and extends into the USA along the Hudson Valley to New York (Kumarapeli and Saull, 1966; Wallach, 2002; Tremblay et al., 2003). Seismic activity away from the SLRS appears to be the result of the reactivation of deeply buried Shield (basement) structures resulting from the Precambrian Grenville Orogeny (1.5 to 1 Ga) now covered by thick (> 1 km) Paleozoic sedimentary strata of Cambrian to Devonian age of the Michigan and Appalachian basins (Onasch and Kahle, 1991; Wheeler, 1995; van Lanen and Mooney, 2007; Baird, 2010). Many examples of faulted Paleozoic strata recording repeated reactivation and upward propagation of basement structures have been found in Southern Ontario (e.g., Sanford et al., 1985; Carter et al., 1996; Eyles et al., 1993; Wallach et al., 1998; Boyce and Morris, 2002).
The historic and instrumental records of earthquakes are relatively short. This places reliance upon the geologic record of seismic activity found as deformation structures (seismites) in Paleozoic sedimentary strata. Much success has also been achieved by examination of lateglacial and postglacial sediments below modern lake floors, and also in regard to the geomorphic record of postglacial seismic activity (e.g., landslides; Adams, 1996; Aylesworth et al., 2000; McAlpin, 2009; Doughty et al., 2010; Mörner, 2011; NRCan, 2011). Ongoing work on joint orientations in glacial sediments and bedrock, the orientation of stream networks and other landscape features such as lake shorelines, together with pop ups (rock bursts) all indicate high horizontal stresses and persistent neotectonic activity related to migration of the North American plate (e.g., Eyles et al., 1997; Jacobi et al., 2007; Doughty et al., 2013). Unfortunately the Paleozoic sedimentary record is incomplete in Southern Ontario but Lower Paleozoic strata (Ordovician to Silurian) of the Michigan Basin are well exposed along the Bruce Peninsula between Georgian Bay and Lake Huron. These strata contain unusual deformation structures that are the focus of this paper.

2.2 STRUCTURAL SETTING OF THE MICHIGAN BASIN

The Michigan Basin is a large almost circular-shaped intracratonic basin about 200,000 km² in extent containing as much as 4.5 km of primarily carbonate and evaporitic deposits of Cambrian through Jurassic age (Fisher et al., 1988; Burgess, 2008; Fig. 2.1). Basin filling began in the late Cambrian with up to 2000 m of siliciclastic deposits of sandstone, shale and sandy dolomites filling a Precambrian structural low broadly related to the Reelfoot Rift (Howell and van der Pluijm, 1990; Catacosinos et al., 1991; Kaminski and Jaupart, 2000).
Warm epeiric seas flooded the basin during the late Cambrian resulting in a dramatic change in depositional style from continental siliciclastic sedimentation to shallow water marine peritidal carbonates principally in the form of thick dolostones (Howell and van der Pluijm, 1999; Burgess, 2008; Miall and Blakely, 2008). Basin subsidence continued until the Middle Ordovician during the Taconic Orogeny coinciding with a late Ordovician basin-wide unconformity (+/- 440-437 Ma) (Catacosinos et al., 1996; Howell and van der Pluijm, 1999). Subsidence, and re-initiated sedimentation, resumed in the Early Silurian with maximum basin subsidence during the Late Silurian and Middle Devonian accommodating more than 3 km of carbonate and evaporitic strata (Catacosinos and Daniels, 1991; Friedman and Kopaska-Merkel, 1991; Kaminski and Jaupart, 2000). Deeper water of the central Michigan Basin was fringed by pinnacle reefs, patch reefs and carbonate platforms (Sarg, 2001; Armstrong et al., 2002; Coniglio et al, 2003). This paper is primarily concerned with mid-Silurian laminated dolostones that accumulated along the northeastern basin margin in a sub-tidal backreef lagoon.

Paleozoic strata of the Bruce Peninsula are underlain by complexly-structured crystalline basement rocks of the Grenville Province added to ancestral North American continental crust between 1.5-1 Ga as two broad belts (Central Metasedimentary Belt (CMB) and Central Gneiss Belt (CGB)). These belts consist of small accreted fault-bounded terranes fused together during the Grenville Orogeny (Carr et al., 2000; Whitmeyer and Karlstrom, 2007; Li et al., 2008). The Grenville Front Tectonic Zone (GFTZ) forms the collisional outer boundary of Grenville crust with older Archean and Proterozoic crust extending northeastwards below the surface of Lake Huron at a depth of about 900m (O’Hara and
2.2.1 Stratigraphy of the Bruce Peninsula

The study area extends over approximately 130 km² of the central Bruce Peninsula of Southern Ontario with field research focussed on outcrops at four quarries located northwest of Wiarton. In addition, correlative horizons were examined in drill core from sites across the Bruce Peninsula from Sauble Falls to Miller Lake (Figs. 2.2, 2.3 and 2.4). The study area is underlain by about 450 m of Ordovician and Silurian strata resting on crystalline Grenville basement about 1 billion years old (Fig. 2.5A; Armstrong, 1993; Armstrong and Carter, 2010). Upper Ordovician strata consist primarily of siliciclastic sediments shed from the Taconic Mountains to the southeast and are unconformably overlain by a succession of Lower to mid-Silurian dolostones and shales (Sanford et al., 1985; Anastas and Coniglio, 1993; Carter and Armstrong, 2010). The uppermost exposed strata of the central Bruce Peninsula study area are dolostones of the Guelph Formation (Armstrong, 1993; Armstrong et al, 2002; Coniglio et al., 2003). The focus of this study is the lowermost part of the Eramosa Member which consists of rhythmically-laminated dolostone. These facies are ‘interbiohermal’, i.e., were deposited between linear reefs of lowermost Guelph and the older underlying Amabel facies (Armstrong and Meadows, 1988). Elongated reef buildups (biohermal mounds) within the Amabel have a preferred orientation of 135° across the Bruce Peninsula and exerted a control on deposition during the subsequent Guelph Formation (Armstrong et al., 2002; Smith and Legault, 1985). These bioherms influenced the
morphology and sedimentology of the then coastal margins creating quiet water enclosed hypersaline lagoons on their landward margins.

Rhythmically-laminated dolostone of the Eramosa Member is quarried at the Big Island, Ebel, Ledgerock and Georgian Bay Marble Quarries and used for decorative polished stone (Fig. 2.3). The unusual intraformational deformation structures in the Eramosa Member and the presence of correlative horizons at widely separated quarries are well known to quarry operators because it affects overall rock quality. What follows are detailed outcrop descriptions of deformed lagoonal laminite facies within otherwise undisturbed Eramosa strata, supplemented by observations of thin sections.

2.2.2 Methodology

Very large cut blocks (1.5 to 2 m$^3$) of deformed laminated facies at the Big Island Quarry were removed for the author by quarry operators. These allowed detailed examination of deformation structures in three dimensions not possible in quarry walls. This data was supplemented by two-dimensional outcrop information from correlative deformation structures that are exposed at three other Wiarton quarries. These were logged in detail. In addition, correlative deformation structures were identified in core samples from oil and gas wells within the central Bruce Peninsula from Sauble Falls to Miller Lake archived at the Oil, Gas and Salt Resources Library in London, Ontario (Fig. 2.5). The study area was expanded by examination of drillcore made available by the Nuclear Waste Management Organization (NWMO) at the Bruce nuclear site near Tiverton, Ontario located some 55 km southwest of the Wiarton quarries (see Geofirma Engineering Ltd., 2011). Thin section samples were
prepared from cut blocks within laminated and deformed horizons from the Big Island Quarry and microscopy was used to evaluate the fine-scale character of the laminae and deformation horizons and to evaluate variation in crystal size and mineralogical composition. What follows is a brief review of sedimentary facies within the Eramosa as a prelude to subsequent descriptions of deformed horizons.

2.3 SEDIMENTOLOGY OF THE ERAMOSA MEMBER

The mid-Silurian Eramosa Member of the Guelph Formation is a very distinctive tan to black coloured, thin to thickly bedded, fine to medium grained crystalline bituminous dolostone (Brunton, 2009; Armstrong and Carter, 2010). It is informally subdivided into four distinct lithological units with the uppermost three units exposed within quarries of the study area (Armstrong and Meadows, 1988; Armstrong, 1993; Fig. 2.6). The lowermost unit, and the focus of this paper, is a distinctive 3-4 m thick sequence of rhythmically-laminated light to dark grey-brown dolostone with an unusual ‘varve-like’ outcrop appearance. These facies were deposited in a backreef sub-tidal quiet water lagoonal setting (Pope et al., 2000; Armstrong et al., 2002; Pratt, 2010) and are locally known as the ‘Marble Unit’ and is as much as 4 m thick. This is well exposed at the Big Island Quarry in vertical cut-face outcrops up to some 300 m in length at the Ebel Quarry, Ledgerock Quarry and the Georgian Bay Marble Quarry (Fig. 2.7AB). Rhythmically-laminated dolostone of the Marble Unit occurs in cores from three sites in the Bruce Peninsula (F014091, T007587 and T0007469; Fig. 2.4).

The base of the Marble Unit consists of gently undulatory domal stromatolitic laminae that progressively flatten upwards into rhythmically laminated facies consisting of
alternating dark (thinner) and lighter (thicker) layers forming distinct ‘couplets’ that range in thickness from 0.01 to 2 cm. Laminae are planar, isopachous (of equal thickness) and laterally continuous (Figs. 2.8AB). Some small-scale deformations (mm to cm scale) are locally present in the form of wrinkles, crenulated laminae, and micro-folds (Figs. 2.9A-D). These small-scale deformations are very limited in lateral extent along quarry walls and do not form stratigraphically correlative horizons across the study area. Laminae in all quarries and core show no evidence of bioturbation, subaerial exposure (e.g., desiccation), or sedimentary structures indicative of unidirectional or oscillatory (wave) bottom currents such as ripple marks or micro-cross-lamination.

Thin section microscopy of laminites shows couplets are composed of alternations of thin (0.26 to 0.61 mm) dark-coloured micritic laminae with lighter coloured, coarser-grained and slightly thicker (0.60 to 0.94 mm thick) laminae of anhedral to subhedral microspar dolomite crystals (0.019 to 0.132 mm diameter) (Figs. 2.10AB). Dark coloured micritic laminae contain small microspar crystals averaging 0.063 mm in diameter. Coarser lighter laminae also display millimetric-thick sub-layers of crudely-graded organic rich bituminous mud alternating with microspar.

The planar isopachous character of correlative laminae across the study area facilitated detailed measurement of couplet thickness to assess potential cyclicity or other temporal patterns indicative of a seasonal or tidal influence. Laminite columns including an affixed measuring tape were photographed and the thickness of each laminae couplet measured and recorded in the laboratory from five locations within the Big Island Quarry, three locations at the Ledgerock Quarry and one at the Ebel Quarry, as well as within drill core T007469. Vertical variation in laminae thickness is similar between each quarry and
within the drill core. The 3.3 m long laminitite section in Core T007469 consists of about 2,400 laminae couplets having an average thickness of 1.3 mm (Fig. 2.11). Laminae thicknesses generally decrease upward through the measured interval. Thin micritic laminae can represent days to even months of accumulation while thicker grainstone laminae may represent sediment or storm accumulation over a much briefer period of time (Tucker and Wright, 1990). It is therefore difficult to assess the time period over which deposition of the Marble Unit occurred and specifically what period of time that one couplet represents. To determine if deposition of Marble Unit laminae was influenced by recurring or repeating sequences of changing environmental conditions, a time-series spectral analysis was performed on laminitite measurement data from core T007469 (Fig. 2.11). Laminae couplet thicknesses were analyzed using “Strati-signal” software to perform both a “fast fourier transform” and “multi-taper” analysis spectral analysis (Ndiaye, 2007; Vaughan et al., 2011). Results of the analyses indicate that the most significant cyclic signal was a sequence of laminae length with a period of about 18 laminae/cycle at a 95% confidence level. The analysis does not suggest a persistent trend or cyclicity. In consequence the timing and frequency of lamina deposition remains unknown.

The Marble Unit has been interpreted as a backreef lagoonal facies deposited in a highly restricted hypersaline shallow marine setting where passive chemical ‘rain out’ processes were dominant over biological processes due to hypersaline conditions (see Pope et al., 2000; Pratt, 2010). The formation of discrete laminae is typical of anoxic stratified benthic environments where rhythmic sedimentation is controlled by changing temperature, salinity, carbonate/saturation precipitation, microbial activity and blooms, among other factors (Davies and Ludlum, 1973; Pope et al., 2000; Riding, 2000; Noffke and Awramik,
Hypersaline and anoxic waters prohibit macrofaunal activity and thus bioturbation is prevented, thereby preserving fine-scale laminae (Tucker and Wright, 1990). Planar laminae within the Marble Unit record deposition in the absence of slope and bottom current influence because delicate laminae could not deposit with significant gravity influences and significant currents would tear laminae or prevent suspension settling or precipitation (Scoffin, 1987; El Taki and Pratt, 2012). The absence of subaerial structures such as desiccation cracks indicates formation of laminae occurred below wave base within a subtidal environment. The Marble Unit is very similar to other younger laminites within the Upper Silurian Salina Group of southwestern Ontario found as reef-capping facies of the A-1 Carbonate and inter-reef laminites of the A-0 Carbonates described by Frizzel (2002) and Coniglio et al. (2004). Coniglio et al. (2004) suggests that occasional near-vertical laminae found within drill core samples of the A-1 and A-0 Carbonates may be generated by synsedimentary earthquakes.

The laminated Marble Unit facies is abruptly overlain by the Middle Unit, a heavily bioturbated light brown coloured, thin to medium-bedded mottled dolostone. The Big Island Quarry exposes 4.5 m of the Middle Unit and displays the abrupt, yet conformable, contact between the laminated and massive bioturbated dolostone units (Figs. 2.7AB). The abrupt contact is displayed in all four Wiarton quarries and is well seen in drill core T007469 located 17 km to the north. It is apparent that the Middle Unit is not a separate stratigraphic unit per se but consists of extensively bioturbated laminites of the same lithology as in the Marble Unit indicating rapid freshening and a sudden return to less restricted marine conditions of normal salinity allowed faunal activity and bioturbation. The abrupt change
between these two facies is of considerable interest in regard to basin subsidence history (see below).

2.4 INTRAFORMATIONAL DEFORMATION STRUCTURES

All quarries in the study area display well-defined intraformational intervals of deformed laminites. These occur in the form of thin (<15 cm) discrete layers of brecciated laminite (BL1 and BL2; Figs. 2.12A-D, 2.13, 2.14A-D) resting on, and overlain by, undeformed laminae. These are found in association with laminated intervals showing small-scale folding (Figs. 2.9A-D). ‘Couplet-counting’ and comparison demonstrates these intervals occur at the same stratigraphic positions in both the Big Island and Ebel quarries. The same brecciated intervals (BL1 and BL2) occur in Core T007469 (Fig. 2.15). A single correlative brecciated layer about 5 to 8 cm thick is displayed at the Ledgerock Quarry. In the Big Island Quarry these intervals are, in turn, deformed by small-scale intraformational thrust faults that die out upwards and are overlain by undisturbed laminae (Figs. 2.16, 2.17). These fault structures are expressed as distinct bumps on exhumed bedding plane surfaces that are exposed across the quarry floor and have a consistent trend (Fig. 2.18). They are clearly intraformational and unrelated to modern days stress-release ‘pop-ups’ that affect surface exposures of dolostones in Southern Ontario (see Adams, 1982; McFall, 1993; Jacobi et al., 2007).
2.4.1 Brecciated laminites and thrust faults

Deformed laminites consist of breccias comprised of small angular clasts (≤5 cm in diameter) of broken laminae that float in a homogenized matrix of highly comminuted laminae fragments (Fig. 2.12BC). These layers are strikingly similar to the facies described elsewhere by Agnon et al. (2006) as ‘intraformational clast breccias’. Those layers in the Big Island Quarry extend across the full 300 m-wide southern quarry wall (Fig. 2.18) and have sharp upper and basal contacts with undeformed laminae above and below (Fig. 2.13). Thin section microscopy shows a homogenized structure consisting of anhedral to subhedral crystals of 0.020 to 0.104 mm diameter with an average of 0.065 mm. The crystal matrix is intermixed with thin fragments of micritic fibre (≤1 mm), torn assemblages of laminae, voids and small infilled fractures (0.08 to 0.2 mm wide). Laminae clasts display the same alternating layers of light microspar and dark micrite as observed within undeformed planar strata (Figs. 2.10CD).

Brecciated laminae layers in the Marble Unit exposed at the Big Island Quarry are, in turn, locally deformed by highly unusual intraformational thrust faults and associated fault propagation folds where overlying beds were pushed up by intraformational faulting (Fig. 2.18). An easternmost structure (Structure A; Figs. 2.18, 2.19A) consists of a gentle anticlinal fold that includes a deformed kink band that can be traced northwards for over 100 m along the exhumed bedding plane that forms the modern quarry floor (Figs. 2.18, 2.19AB). About 60 m to the west of Structure A is a fold-fault structure (Structure B; Figs. 2.16, 2.18) composed of an asymmetrical anticlinal fold with a steep eastern limb and a gently sloping western backlimb (Fig. 2.20A) that together define a reverse thrust fault tip (Fig. 2.16). A triangular zone of contorted and overturned folded laminae radiates upwards from the steep
easterly forelimb and fault tip (Figs. 2.20BC). The lower portion of the fault is exposed 3 m to the north of the quarry wall revealing rolled bedding suggestive of fault drag (Fig 2.20D). Structure B occurs as a sinuous ridge on the quarry floor that is more than 30 m in length (Fig. 2.20E) and is also exposed in a now-closed quarry to the north indicating the structure is at least 400 m in length. Small fluid escape structures, dykes and folds are associated with faults (Figs. 2.21AB).

As related above, breccia layers are of wide geographic extent across the Bruce Peninsula. Layers, correlative with those exposed in the Big Island Quarry (BL1 and BL2) occur 2.5 km to the southeast at the Ebel Quarry and the Marble Unit at Ledgerock Quarry 1.7 km south of the Big Island Quarry, display one of the two breccia layers (Fig. 2.14C) which re-occurs in the Georgian Bay Marble Quarry (Fig. 2.14D). Drill cores with stratigraphically correlative breccia layers occur in Core T007587 11 km to the south and 17 km to the northwest of Big Island Quarry in Core T007469. These horizons are therefore demonstrated to occur over an area of at least 130 km² of the central Bruce Peninsula, and possibly much more. The Eramosa Member is absent from the Guelph Formation in NWMO core drilled at the Bruce nuclear site (DGR-1-6; see Geofirma Engineering Ltd., 2011) some 55 km to the southwest of the Wiarton quarries.

2.4.1.1 Origin of breccias and faults

Breccias and small-scale folds are interpreted as the product of abrupt events that interrupted otherwise quiet-water lagoonal deposition of laminae (Calvo et al., 2007; Agnon et al., 2006; Martin-Chivelet et al., 2011). This involved in-situ liquefaction of laminae lying at and just
below the seafloor to produce breccias; lateral slip is clearly indicated by folds and it is possible that breccias could record lateral flowage of liquefied slurries, but this cannot be clearly demonstrated by any characteristic internal flow fabric. Brecciated intervals of laminated sediments could be attributed to a number of processes such as storms, gravity related slumping, bioturbation, microbial mounding, overloading of sediments as well as ground shaking caused by earthquakes (Moretti et al., 1999; Noffke et al., 2001; Martin-Chivelet et al., 2011; Sims, 2012; Van Daele et al., 2014). Delicate laminae were deposited in a hypersaline flat-lying depositional environment thus precluding gravitational slumping or bioturbation as a primary cause of deformation. Deformation triggered by storm waves or rapid sedimentation is an unlikely cause of brecciation due to the absence of current-related structures and sediments. All homogenized breccia layers encountered in outcrop and core are bounded above and below by undeformed laminated strata indicating both a sudden initiation and a sudden cessation of debris flow. Therefore the only remaining trigger likely for generating the homogenized breccia layers is seismic shaking (e.g., Wheeler, 2002; Jewell and Ettensohn, 2004; Montenat, et al., 2007; Owen et al., 2011; Van Dael et al., 2011). In this regard, it is significant that the intraformational breccias of the Eramosa are similar to seismites identified within the rhythmically-laminated late Pleistocene Lisan Formation of the Mt. Sedom region of the Dead Sea Rift, an area of well documented seismicity and co-seismic deformation of lacustrine sediments. Such deposits include numerous silt clast breccias recording liquefaction and remobilization of the lake floor (e.g., Marco and Agnon, 1995; Agnon et al., 2006; Fig. 2.22AB).

The wide spatial extent of correlative debrite horizons (BL1, BL2) in the Bruce Peninsula as clearly established from quarry outcrops and correlative drill core sections
indicates that sediment gravity flow affected a large area (at least 130 km²). These facies are highly unusual, unlike any facies occurring below or above within the Guelph Formation; a rapid return to low energy background conditions is indicated by overlying undisturbed laminated couplets. These were then deformed by thrusting and faulting, before a return once again to ‘quiet water’ conditions dominated by low energy suspension settling. By analogy with comparable deformation structures reported elsewhere, and the broad spatial extent of deformed Eramosa Member facies in the Wiarton area, it is argued that deformation is the product of repeated seismicity and shaking and remobilization of the sea floor. Laminae are typically deposited on slopes less than 1° thus requiring a sudden reduction in shear strength and a trigger other than gravity to destabilize and move the sediments (Martin-Chivelet et al., 2011; Alsop and Marco, 2012). Laminated couplets were likely liquefied in situ by seismic activity and remobilized as slurries in which clasts of coherent laminated facies floated within a fluidized matrix.

The close relationship between the brecciated layers and intraformational faulting is of great significance as it suggests a common earthquake-related origin. Reverse thrust faults with associated fault-propagation folding deform the brecciated laminae layers at the Big Island Quarry (Figs. 2.16, 2.23). These are best displayed within the westernmost structure (Structure B) where a reverse fault tip propagated upwards and is delineated by folding around the tip (e.g., Williams and Chapman, 1983; Chester and Chester, 1990; Fossen, 2005). ‘Text book’ kink band folds converge at the anticlinal fold accompanying trishear deformation distributed outwards from the propagating fault tip (e.g., Erslev, 1991; Twiss and Moores, 2007; Fossen, 2010). This is expressed by a triangular fold zone and fault drag beneath the fault ramp (Figs. 2.20D, 2.23). Undisturbed horizontally-bedded laminae lie
above these deformed structures confirming that deformation was intraformational (Fig. 2.20B). At the Big Island Quarry fault tips propagate upwards from a basal detachment fault (decollement) below the quarry floor and are expressed through sequences of tip line folds (Structures A and B). Thrust faulting in an otherwise passive intracratonic setting is attributed to compression along the toes of large slumps mobilized by earthquake activity. This is in keeping with the recognition of thin horizons of debrites (silt clast breccias) at the same stratigraphic intervals which may have been triggered by slope failure. The association between seismically triggered, stratigraphically-related thrust faults produced by slumping, with chaotic and contorted laminae produced by debris flow, as well as fluid escape structures and kink band deformations similar to those described herein are commonly displayed within Lisan sediments of the seismically active Dead Sea (e.g., Agnon et al., 2006; Alsop and Marco, 2011; Figs. 2.22CD). In the case of the Bruce Peninsula, slumping, faulting and remobilisation of laminated lagoonal sediments likely occurred from the flanks of high standing biohermal mounds which defined the margins of lagoons along the coast. Thrust faulting clearly postdates debris flow activity in the studied quarries and this might suggest multiple phases of slumping are recorded within the Eramosa Member indicating persistent seismicity in the study area.

In view of the above interpretation of the paleoenvironmental significance of deformation structures exposed in the Eramosa Member near Wiarton, debrites and related intraformational thrust fault structures are identified as ‘seismites.’ This term was introduced by Seilacher (1969) to refer to beds in either siliciclastic and carbonate rocks that have been deformed by ground shaking during earthquakes. Seismites include a wide array of soft-sediment deformation structures such as breccias, folds, and convoluted bedding, and brittle
deformation structures such as faults (e.g., Pratt, 1994; Pope et al., 1997; Ettensohn et al., 2002; Greb and Dever, 2002; Merriam and Forster, 2002). In this regard, deformation structures within laminated carbonates, similar to those described here, are confirmed as seismites from correlative Paleozoic strata in adjacent parts of mid-continent North America (e.g., Kahle, 2002; El Taki and Pratt, 2009; El Taki and Pratt, 2012). These are discussed below in the context of the subsidence history of the Michigan Basin and the role of basement fault reactivation.

### 2.5 DISCUSSION

The interpretation made herein of a seismic origin for unusual intraformational deformation structures (breccias, faults) discovered in mid-Silurian laminites of the central Bruce Peninsula, Canada is supported by the presence of similar structures documented in stratigraphically-correlative Silurian strata in adjacent parts of the Michigan Basin in the U.S. (Fig. 2.1). It is regarded as being highly significant that the same deformed facies of intraformational breccias associated with folds and faults are documented within mid- to Upper Silurian laminated dolostones in western Ohio and southeastern Michigan some 500 km southwest of the Bruce study area (see Onasch and Kahle, 2002; Figs. 2.1, 2.3B). These lie within 30 kms of the Grenville Front Tectonic Zone and have been interpreted as seismites related to the reactivation of the Grenville Front Tectonic Zone (Onasch and Kahle, 2002). This is of considerable interest as the Bruce Peninsula lies immediately east of the same structure indicating a common origin for Silurian seismites both west and east of the GFTZ. If these various structures are correlative, this suggests a very wide spatial extent of
co-seismic deformation during a series of large earthquakes. In this regard, spatial extent provides an approximation of earthquake magnitude.

It is generally accepted that the minimum magnitude earthquake required to liquefy seafloor sediments is M5; liquefaction features are rare for earthquakes of less than M5.25-5.5 (see Ambraseys, 1988; Moretti et al., 1999; Kahle, 2002). This is supported by data from Israel where deformation of similar laminated sequences within the Lisan Formation in the Dead Sea Rift is associated with a minimum magnitude M5.5 earthquake (Marco and Agnon, 1995; Agnon et al., 2006). The same broad relationship has been established by Ambrasays (1988) who demonstrated the relationship between liquefaction, earthquake magnitude and epicentral distance (radius) in Holocene continental sediments (Fig. 2.24) and for seismites within siliciclastic and carbonate sediments of Ordovician and Silurian age within the Appalachian Basin (e.g., Pope et al., 1997; Ettensohn et al., 2002; Jewell and Ettensohn, 2004). If it can be assumed that the deformation structures described are related to reactivation of the Grenville Front Tectonic Zone then an epicentral distance of at least 50 km is indicated. This suggests that an earthquake of at least magnitude M7 deformed the Marble Unit sediments. Interestingly, modern seismic risk analysis for the Southern Ontario region considers an M7 earthquake to be plausible and is modelled as a 1/500 year event (AIR Worldwide, 2013). Modern and ancient data regarding potential earthquake magnitudes are thus in broad agreement. The implications for assessing modern day seismic risk are briefly explored in a later section.

Deformation structures described from the Bruce Peninsula and those correlative structures in the US coincide with a phase of rapid subsidence of the Michigan Basin. Far-field compressional stresses generated along the eastern active margin of the North American
plate during successive Appalachian orogenies resulted in differentiation of broad foreland basins in mid-continent and associated uplift of basement highs such as the Algonquin and Findley Arches that pass through Southern Ontario (Sanford et al., 1985; Howell and van der Pluijm, 1990; Miall and Blakey, 2008). Sanford et al. (1985) mapped basement faults in Southern Ontario and showed they had been active and been propagated up through overlying Paleozoic strata in the time interval from the Silurian through to the Lower Devonian (Fig. 2.5C). Sanford et al. (1985) argued that basement reactivation was expressed regionally by differential tilting of individual fault-bounded ‘megablocks’ (his term) of Paleozoic strata such as the Bruce and Niagara ‘blocks’ of southwestern Ontario. It is known that the Michigan Basin experienced episodes of varying subsidence rate (Burgess, 2008), initially during the Early to Middle Ordovician and subsequently during the Silurian (e.g., Howell and van der Pluijm, 1999; Kaminiski and Jaupart, 2000). This includes the timeframe recorded, in part, by the Guelph Formation and Eramosa Member in Southern Ontario. Vein calcite analysis of Paleozoic strata in the vicinity of Bruce Nuclear Generating Facility, located less than 20 km from the Grenville Front Tectonic Zone (GFTZ), reveals that fractures and veins within Ordovician strata (445 +/- 42 Ma) formed shortly after deposition suggesting fluid precipitation occurred during periods of extension, uplift or seismic disturbance (Davis, 2013). Fracture formation corresponds with sequences of Arch uplift and rapid subsidence of the Michigan Basin (Sanford et al. 1985).

Further evidence of far-field stress propagation into that part of the Michigan Basin being studied here is forthcoming from the orientation of linear mid-Silurian biohermal mounds across the Bruce Peninsula. These display a preferred orientation of 135° within the Amabel Formation almost in perfect agreement with the strike of the faults reported here.
within the Eramosa Member (Smith and Legault, 1985). In summary, it is likely that seismites reported here from the Bruce Peninsula can be attributed to basement reactivation arising from far-field Appalachian stresses at a time of enhanced subsidence of the Michigan Basin. The dramatic change in facies from rhythmically-laminated dolostones of the Marble Unit of the Eramosa Member to the heavily bioturbated laminated mottled dolostone of the Middle Unit is also of significance. This may be due to a re-configuration of coastal morphology following co-seismic subsidence allowing ingress of lower salinity waters and repopulation of the sea floor by bottom-dwelling and burrowing organisms.

Finally, it is worth emphasizing that the deformation structures (seismites) described here can with some degree of confidence be attributed to reactivation of a specific basement structure (GFTZ). This finding is in keeping with interpretations of analogous and stratigraphically equivalent Silurian seismites in adjacent parts of the Michigan Basin and indicates that the GFTZ was a source zone for large and possibly persistent earthquakes during basin subsidence.

**Implications for understanding modern intraplate seismicity**

Although the precise mechanisms for modern intraplate earthquakes in Ontario remain poorly understood, they are widely modeled as a result of the reactivation of old brittle basement structures related to the assembly of the Canadian Shield as the North American plate moves westward (Adams and Basham, 1989; Stein and Mazzotti, 2007; Baird, 2010; Bartholomew and Van Arsdale, 2012). Modern earthquakes occur 50 to 100 times more frequently along former sutures and paleo-rift systems than elsewhere within the Canadian Shield as a whole, though this too may reflect an absence of data (Mazzotti, 2007; Liang and
The same structures that may have influenced the configuration and subsidence of the Michigan Basin are potentially active today. This study has identified the likely importance of the Grenville Front Tectonic Zone, but there are numerous other structures that pass close by the Bruce Peninsula. Boyce and Morris (2002) mapped additional aeromagnetic and gravity lineaments below the Bruce Peninsula (Fig. 2.25) including the northwestward trending Georgian Bay Linear Zone (GBLZ) that defines the eastern shore of Georgian Bay along with another north-south trending major gravity lineament immediately east of the study area. Neither of these lineaments is well understood. Two additional minor northwest trending aeromagnetic features also lie within the Wiarton area. The Bruce Peninsula has experienced numerous small earthquakes in the very recent past with a total of 35 events recorded from 1991 to 2003. All these events occurred within 100 km of the study area. A recent M4.3 earthquake in 2005 (Fig. 2.25) was described as the strongest locally recorded earthquake in the Great Lakes area of Southern Ontario (Dineva et al., 2007; Earthquakes Canada, 2013); its epicentre was about 60 km east of the Wiarton study area. In this regard, it is highly significant that deformation horizons within mid-Silurian strata interpreted here as seismites occur in close proximity to basement structures that are active at the present day. However, the instrumental record is very short (< 100 years) and evaluation of seismogenic structures from seismites in the rock record is required along the lines reported here. This is of particular importance due to the relative proximity of the Bruce Nuclear Generating Station and the proposed Deep Geologic Repository for low level nuclear wastes to the GFTZ and other structures. Nuclear generating stations also occur east of Toronto at Pickering and Darlington close to another first-order Precambrian basement structure. This underscores the need for further exploration of the stratigraphic and
sedimentologic record of earthquakes in Paleozoic and glacial strata in Southern Ontario (Chapters 3, 4).

2.6 SUMMARY AND CONCLUSIONS

Outcrops of Silurian laminites over an extensive portion of the central Bruce Peninsula study area display unusual syndepositional thrust faults and propagation folds that affect layers of intraformational clast breccias. Deformation structures are interpreted as seismites and attributed to reactivation of the GFTZ in the mid-Silurian at a time of enhanced subsidence of the Michigan Basin generated by far-field stresses during the Appalachian Orogeny. This study confirms, for the first time, the presence of seismites within the Paleozoic deposits of the Michigan Basin within Southern Ontario similar to those described from adjacent areas of the Appalachian and Michigan basins in Michigan, Ohio and Kentucky of the U.S.

Evaluation of seismites and their distribution within the Michigan and Appalachian Basin deposits of Southern Ontario is an essential step in establishing the relationship between paleoseismicity and reactivation of buried structures within areas of modern intraplate earthquake activity such as the Georgian Bay area and the heavily populated western Lake Ontario region.
Figure 2.1  Major tectonic elements and structures of Southern Ontario. CMBBZ – Central Metasedimentary Belt Boundary Zone. GFTZ-Grenville Front Tectonic Zone; CMBBZ-Central Metasedimentary Belt Boundary Zone. Hashed rectangle indicates study area (after Armstrong and Carter, 2010 and Boyce and Morris, 2002 and references therein).
Figure 2.2  Study area location. Shaded areas show areas of contemporaneous Silurian seismites within mid-continent U.S. (see Onasch and Kahle, 2002).
Figure 2.3 Wiarton area quarries.
Figure 2.4  Drill core samples and quarry locations.
**Figure 2.5**  Stratigraphic columns for Ordovician-Silurian deposits. A: Stratigraphy of the Bruce Peninsula indicating seismites with the Eramosa Member (after Armstrong et al., 2002). B: Silurian stratigraphy indicating seismites of the mid-continent U.S. (after Onasch and Kahle, 2002). C: Tectonic movements during the Silurian of Eastern North America (after Sanford et al., 1985).
Figure 2.6  Lithological units of the Eramosa Member in the Wiarton area of the Bruce Peninsula (after Armstrong and Meadows, 1988).
Figure 2.7  Dolostone units of the Eramosa Member exposed at the Big Island Quarry, Wiarton, Ontario. A: Upper unit of non-laminated “Middle Unit” dolostone overlying laminated “Marble Unit”. Sharp contact indicated with arrow. B: Sharp contact between non-laminated “Middle Unit” dolostone overlying laminated “Marble Unit”.
Figure 2.8  Planar, regular, continuous and isopachous laminae within laminated Marble Unit at Wiarton quarries. A: Big Island Quarry. B: Ebel Quarry.
Figure 2.9  Small-scale deformation structures in Eramosa Marble Unit in Wiarton Quarries. A: Micro-fold, Ledgerock Quarry. B: Pinch and swell features, Georgian Bay Marble Quarry. C: Small-scale folds, Ledgerock Quarry. D: Micro-folds and pinch and swell structures, Ledgerock Quarry.
Figure 2.10  Thin-section photomicrographs (Big Island Quarry) using plane-polarized light (unstained). A: Undeformed laminations indicating coarser microspar laminae (a) alternating with micritic laminae (b). B: Upper bounding laminations directly above upper deformation horizon indicating undeformed laminations of coarser microspar laminae (a) alternating with micritic laminae (b). C: Lower brecciated layer (BL1) displaying homogenized crystal matrix and fibrous pieces, includes crystallized fracture. D: Upper brecciated layer (BL2) displaying homogenized crystal matrix. Arrow indicates “torn” piece of micritic laminae.
Figure 2.11  Measurements of laminae couplet thicknesses, drill core T007469.
Figure 2.12  Photographs of brecciated layers at Big Island Quarry. A: Upper and lower brecciated layers. B: Homogenized deformation in upper brecciated layer (BL2). C: Turbulent style of deformation in upper brecciated layer (BL2). D: Bed separation at basal boundary of upper brecciated layer (BL2) circled.
Figure 2.13  Photograph of lower brecciated layer (BL1) at Big Island Quarry.
Figure 2.14  Photographs of brecciated layers at Wiarton Quarries. A: Lower brecciated layer at Ebel Quarry. B: Upper and lower brecciated layers at Ebel Quarry. C: Brecciated layer Ledgerock Quarry. D: Brecciated layer at Georgian Bay Marble Quarry.
Figure 2.15  Brecciated layer within rock core T007469 from 1.75 to 1.88 m below top of laminated horizon.
**Figure 2.16** Intraformational thrust fault-fold propagation structure (Structure B) located along south wall of Big Island Quarry.
Figure 2.17  Sketch of deformation features and stratigraphy at Big Island Quarry.
Figure 2.18  Location of intraformational deformation exposures along southern wall of Big Island Quarry. Linear trends on quarry floor (with orientations) are shown.
Figure 2.19  Deformations at southern wall (Structure A). A: Anticlinal fold and kink band. B: Folding 25 m north of south wall.
Figure 2.20  Photographs of intraformational fault propagation fold deformation structures. A: Anticline and brittle fracturing at kink band folds. B: Deformed beds at upper extent of eastern trace overlain by undisturbed laminae. C: Brittle fracturing in contorted upper beds. D: Deformation 3 m north of south wall feature indicating drag along the fault. E: Sinuous ridge along quarry floor leading to thrust fault feature to the south.
Figure 2.21  Photographs of contorted and chaotic laminations in central portion of the quarry. A: kink band and fluid escape structure. B: contorted and chaotic bedding.
Figure 2.22  Comparison of deformed laminae within the Eramosa (Wiarton, Ontario) and the Lisan Formation (Dead Sea Rift). A: Homogenized breccia layer, Big Island Quarry, Wiarton, Ontario. B: Intraclast breccia horizon (seismite), Mt. Sedom, Israel. C: Chaotic bedding, Big Island Quarry, Wiarton, Ontario. D: Chaotic deformations, Lisan Formation, Mt. Sedom, Israel.
Figure 2.23  Reverse-thrust fault and propagation fold structure along south wall of Big Island Quarry. Structure indicating fault tip and zone of trishear deformation.
Figure 2.24  Relationship of earthquake magnitudes and epicentral area (after Allen, 1986; Ambrasays, 1988; Pope et al., 1997 and references therein).
Figure 2.25  Aeromagnetic and gravity lineaments in Southern Ontario including the Bruce Peninsula area including earthquake epicentres (after Boyce and Morris, 2002; Doughty et al., 2014; and references therein). Relationship of earthquake magnitudes and epicentral area (after Allen, 1986; Ambrasays, 1988; Pope et al., 1997 and references therein). GFTZ: Grenville Front Tectonic Zone; CMBBZ: Central Metasedimentary Belt Boundary Zone; NPLZ: Niagara-Pickering Linear Zone; HLEL: Hamilton-Lake Erie Lineament; HPL: Hamilton-Presqu’ile Lineament; GBLZ: Georgian Bay Linear Zone.
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CHAPTER 3:  
SEISMITES WITHIN ORDOVICIAN-SILURIAN SILICICLASTIC AND CARBONATE SHOREFACE STRATA OF SOUTHERN ONTARIO, CANADA

ABSTRACT

A systematic survey of Lower Paleozoic shoreface sandstones, shales, and dolostones (Ordovician-Silurian) in outcrop and drill core from Southern Ontario, Canada was conducted to determine the sedimentary record of paleo-seismicity during subsidence of the Appalachian Basin. The study identifies laterally-extensive beds of large (< 2 m) synsedimentary ball-and-pillow structures in outcrops hundreds of metres long within the Lower Silurian (c.439-441 Ma) Thorold Formation. Deformation structures are continuously exposed across an area of 5 km² along the Niagara Escarpment near Hamilton at the western end of Lake Ontario. Deformation structures occur within interbedded upper and middle shoreface sandstones and shales that mark the end of prograding clastic shelf deposition and the subsequent transition to transgressive shallow marine deposition accompanying an increase in relative water depths. Ball-and-pillow structures are the product of the rapid foundering of sand into underlying mud and are similar to earthquake-generated structures produced experimentally and recorded from Holocene sediments. Drawing on the wider literature it can be argued that the Thorold Formation seismites record ground shaking over a broad swath of what is now the western Lake Ontario area by a moderate earthquake with a magnitude of at least M6. They are very similar to other reported seismites of this age in Michigan, Ohio and Kentucky which are attributed to reactivation of Precambrian basement structures and rapid subsidence of the Appalachian basin during successive Appalachian
orogenies. Other deformation structures identified in the present study include large ball-and-pillows within the sandstone-shale successions of the Upper Ordovician Georgian Bay Formation and the Lower Silurian Grimsby Formation, as well as severely contorted and convoluted bedding of the Lower Silurian DeCew Formation, suggesting that the western Lake Ontario and Niagara Peninsula regions experienced recurrent seismicity from the Upper Ordovician through mid-Silurian, likely related to complex basement structures and poorly understood geophysical lineaments. These structures are active at the present day.
3.1 INTRODUCTION

Central Canada is affected by recurring low to moderate (M5-6) intraplate earthquakes that have caused millions of dollars of damage including the Cornwall, Ontario M5.8 earthquake of 1944 which was the costliest earthquake to date in Canada (Adams and Basham, 1989; Wallach et al., 1998; Mazzotti and Adams, 2005; Cassidy et al., 2010; NRCan, 2011). Unfortunately the causes of these intraplate earthquakes are poorly understood but are thought to be the product of reactivation of Precambrian structures often buried below thick Phanerozoic strata (Mazzotti, 2007). The relationship between intraplate seismicity and the reactivation of buried structures is of particular interest in the densely populated Southern Ontario which experiences recurring low to moderate intraplate earthquakes and is underlain by a complexly structured Precambrian basement (Fig. 3.1). Seismic-hazard assessment in the area is impeded by a short historical record (generally since the early 1800’s), an even shorter instrumental record (last 100 years), and the lack of expression of surface faults whose evidence was stripped by repeated glaciations (Adams and Basham, 1989; Adams, 1996). Despite these problems there is widespread evidence of the persistent influence of reactivated Precambrian basement structures during deposition of Paleozoic cover rocks reactivated by far-field stresses during successive Appalachian orogenies (Sanford et al., 1985). The same structures are also implicated in the generation of faults in relatively young late glacial (11-10,000 years before present) and postglacial (< 10,000 ybp) lacustrine sediments (e.g., Shilts and Clague, 1992; Doughty et al., 2010a; Doughty et al., 2010b; Doughty et al., 2013; this thesis chapter 4). There is also a marked Precambrian structural control on topography and drainage patterns (Eyles et al., 1993; Eyles and Scheidegger,
1995) which has also influenced the distribution of stress release features in bedrock (pop- ups; Jacobi et al., 2007). Previous investigation of Paleozoic strata in terms of earthquake activity has been limited to brief descriptions of “possible” seismites within outcrops of Upper Ordovician through mid-Silurian strata (e.g., Martini, 1971; Friedman et al., 1982; Duke, 1991; Kerr and Eyles, 1991; Brunton, 2009; Armstrong and Carter, 2010; Fig. 3.2; Table 3.1).

3.1.1 Purpose of this paper

This paper is part of a broader study aimed at a systematic examination of Paleozoic and Pleistocene glacial and postglacial strata in Ontario to identify geologic evidence of paleoseismicity (Chapters 2, 4 and 5). The purpose is to identify underlying basement structures having a persistent history of reactivation; this information is required to inform ongoing assessments of seismic risk in Canada’s most populated area. Some workers have suggested a seismic origin for many soft sediment deformation horizons in certain Paleozoic strata (e.g., Martini, 1971; Friedman et al., 1982; Duke, 1991; McLaughlin and Brett, 2006; Armstrong and Carter, 2010) but until the present study reported here no systematic or comprehensive survey has been conducted. This prompted a systematic survey of outcrops and drill core in Southern Ontario, especially along the length of the Niagara Escarpment guided by detailed descriptions of seismites recorded in correlative Paleozoic strata in the adjacent U.S. related to reactivation of the Precambrian Grenville Front Tectonic Zone (GFTZ) and the Cincinnati Arch (e.g., Pope et al. 1997; Ettensohn et al., 2002; Greb and Dever, 2002; Onasch and Kahle, 2002; Jewell and Ettensohn, 2004). Sequences of alternating shoreface sandstones and
thin shale interbeds comprise a large cumulative thickness of strata in Southern Ontario and it is in such strata, with widespread opportunity for reverse density contrasts and loading of sand into mud, that the effects of co-seismic ground shaking are likely to be most clearly expressed. This paper contributes to the discussion of paleo-seismicity in Southern Ontario by identifying and describing deformation structures in Ordovician and Silurian strata which provide compelling evidence of severe ground shaking. The broader significance of this work in terms of underlying Precambrian basement structures and their relation to ongoing mid-plate seismicity is briefly discussed.

3.1.2 Methodology

A systematic field survey of thirty-two different outcrops of Ordovician and Silurian shoreface strata was conducted across a 7,000 km² study area of Southern Ontario (Figs. 3.2, 3.3, and 3.4). The total cumulative stratigraphic thickness examined is of the order of about 150 m. Four stratigraphic units were subsequently identified as displaying deformation structures in sandstones and dolostone that could reasonably be interpreted as seismites. These are the Upper Ordovician Georgian Bay Formation and the Lower Silurian Thorold, Grimsby, and DeCew Formations. These were studied in outcrops exposed principally along the length of the Niagara Escarpment and Niagara Gorge, and more sporadically at road and stream cuts within the western Lake Ontario region. Oil and gas well logs within the Oil, Gas and Salt Resources Library database were reviewed with the purpose of identifying deformed horizons within Thorold and Grimsby Formation sub-surface strata. Thorold strata was encountered at 105 locations, of which drill core samples were available for examination from thirteen of these locations across the Niagara Peninsula and north eastern Lake Erie.
(Fig. 3.3). The Thorold core was examined, logged and photographed. The thickness of subsurface Thorold strata ranges from 2.5 to 5 m and occurs at depths of 45 m near the Niagara Gorge (core F014222) and up to depths of 500 m below Lake Erie (core T003829; Fig 3.3). Structures in outcrops and drill core were evaluated using well established interpretive criteria for seismites (e.g., Wheeler, 2002; Owen et al., 2011; Figs. 3.2 and 3.3). What follows is a brief description of the regional stratigraphic framework.

3.2 OVERVIEW OF REGIONAL PALEOZOIC STRATIGRAPHY

The complexly-structured Precambrian crystalline basement rock of Southern Ontario is unconformably overlain by up to 1,400 m of Cambrian through Devonian sedimentary strata belonging to the Appalachian and Michigan basins (Armstrong and Carter, 2010; Fig. 3.1). Deposition across what is now Southern Ontario occurred at the margins of these two basins and was influenced by the Algonquin Arch, a large bulge in the basement (Leighton, 1996; Howell and van der Pluijm, 1999; Fig. 3.1). The Late Ordovician and Early Silurian Taconic Mountains in Appalachia were the source of large volumes of clastic sediment which were moved to the north and northeast by large rivers into what is now Southern Ontario to form a thick (12 km) northwestward-thinning clastic wedge. The Algonquin Arch effectively forms the western limit of the basin in Southern Ontario where Paleozoic strata thin to 500-1,000 m (Middleton, 1982; Milici and de Witt, 1988; Cheel, 1991; Benincasa, 1996; Brett et al. 1998). This paper is primarily concerned with the Upper Ordovician Georgian Bay Formation, Lower Silurian Grimsby, Thorold and DeCew Formations (Table 3.1) all of which are shoreface successions of shale and sandstone. The most impressive evidence of co-seismic shaking occurs near Hamilton in the Thorold Formation which is a sequence of marine
sandstones and shale deposited in a storm-influenced shallow marine setting (Friedman et al., 1982; Rutka, 1985; Rouble, 1991; Brett et al., 1995; Beninscasa, 1995). Early workers (Liberty, 1957) as well as Armstrong and Carter (2010), assigned the Thorold to the overlying Clinton Group while some later workers (Brett et al, 1995) suggest the strata conformably overlies the Grimsby Formation as part of the Cataract Group (Fig. 3.4). What follows is a description of an extensive horizon of deformed ball-and-pillow structures found within otherwise undisturbed strata of the Thorold Formation.

3.2.1 Sedimentology and depositional history of the Thorold Formation

The Niagara Escarpment is the dominant physiographic feature of Southern Ontario. It forms a southwest dipping cuesta capped by resistant Silurian Guelph Formation dolostones, and is as much as 80 m high. It exposes Upper Ordovician through mid-Silurian strata extending from the Niagara River northwards through to the northern tip of the Bruce Peninsula (Rutka, 1986; Tovell, 1992; Fig. 3.2). This study examined outcrops of the Lower Silurian Thorold Formation along the Niagara Escarpment exposed over a distance of some 20 km between the communities of Ancaster and Stoney Creek (Figs. 3.2 and 3.3). Detailed field work focussed on long continuous outcrops exposing deformed Thorold strata between Upper James Street and Mountain Brow Boulevard near Hamilton (Fig. 3.5). In this area, outcrops of Thorold deformation structures were studied at four easily accessible locations where roads traverse the face of the escarpment through deep cuts; at the Claremont Access, the Jolley Cut, the Sherman Access and the Kenilworth Access (Fig. 3.5). Deformation structures are well exposed in sidewalls of these road cuts.
The Thorold Formation (439-441 Ma) comprises sheet like, grey-green to white, fine to coarse-grained quartzose and lenticular-shaped sandstones with minor thin grey to green shale and siltstone interbeds (Martini, 1971; Duke, 1987; Johnson et al., 1992; Brett et al., 1995; Armstrong and Carter, 2010). It was deposited in an upper to middle shoreface environment within the developing Taconic foreland basin (Martini, 1974; Rutka, 1986). The Thorold is of relatively restricted thickness across the study area ranging from 1.4 to 4 m and pinches out immediately to the northwest of Hamilton (Kilgour and Liberty, 1981; Friedman et al., 1982; Johnson et al., 1992; Brett et al., 1995; Armstrong and Carter, 2010). A storm influenced shallow-water marine environment is recorded by sedimentary structures such as hummocky cross-stratification and common wave ripple cross-laminated facies (Middleton, 1982; Johnson et al., 1992). Sandstones contain an abundance of marine trace primarily of *Cruziana* ichnofacies (Pemberton, 1987).

### 3.3 POST DEPOSITIONAL DEFORMATION STRUCTURES

Unusual and very large synsedimentary ball-and-pillow structures affect a single sandstone bed within the Thorold Formation exposed over some 5 km of the face of the Niagara Escarpment (Figs. 3.5, 3.6AD). At other outcrops visited the Thorold Formation was either not exposed or no deformations structures were observed (Fig. 3.3). No evidence of ball-and-pillow deformation was identified in the thirteen cores examined suggesting that deformation was limited to the northern portion of the study area in the Hamilton-western Lake Ontario region (Fig 3.3). The ball-and-pillow horizon is abruptly overlain by flat-lying, sharp-based, undeformed sandstone beds ranging in thickness from 5 to 20 cm thick (Figs. 3.6AD and 7AB). Rounded and deformed sandstone pillows, ranging from 0.2 m diameter nodules to
large hemispherical pillows 2 m in diameter, are surrounded by a deformed homogenized shale/matrix that forms upward narrowing diapirs between sandstone pillows indicating foundering of sandstone into a muddy substrate (Figs. 3.8A to D; 3.9AB). Pillows display internally-convoluted lamina indicative of post depositional hydroplastic deformation (Pope et al., 1997; Figs. 3.9AB; 3.10) and rare vestigial bedding suggests original hummocky stratification. Large rounded, internally contorted, hemispherical sandstone pillows rest at seemingly indiscriminate angles with no preferred orientation on the top of underlying sandstone (Pope et al., 1997; Fig. 3.11). Pillow structures are clearly the result of widespread loading of a single stratigraphic horizon into muddy sediments below (e.g., Potter and Pettijohn, 1977; Bartlett and Youd, 1992; Allen, 1982; Collinson, 2003; Obermeier, 1995; Owen 2003; Fig. 3.12). Loading was clearly highly unusual and affected a single stratigraphic surface suggesting an abrupt triggering event. Storm waves are also known to trigger extensive soft-sediment deformation on shallow marine shorefaces as a result of strong cyclic changes in pore water pressures but the considerable (5 km) lateral extent and stratigraphically-restricted occurrence of ball-and-pillows in the Thorold suggests this is an unlikely mechanism. Furthermore, a large storm would be expected to generate strong bottom currents and to cut shoreface channels and gutter casts filled with rippled and cross-stratified sandstone facies; these are notably absent from the deformed Thorold interval which consists of relatively simple alternations of lenticular sandstone and shale interbeds. The deformed horizon is abruptly and consistently, overlain by undisturbed flat-lying sandstone indicating a rapid return to normal shallow marine conditions. Deformation clearly occurred in-situ with no evidence of horizontal displacement such as by mass flow or thrusting (e.g., Davenport and Ringrose, 1987; Alsop and Marco, 2011).
The only remaining likely trigger for the formation of the ball-and-pillows is co-seismic shaking (e.g., Maltmann, 1994; Pope et al., 1997; Sims, 2012). Kuenen (1958) which demonstrated in the laboratory that ground shaking resulted in loading of sands into thixotropic clay (Fig. 3.13). Geographically extensive horizons of ball-and-pillow structures occur and at many locations in other Paleozoic strata within the Michigan and Appalachian basins of Michigan, Ohio, Kentucky and Virginia (e.g., Potter and Pettijohn, 1977; Pope et al., 1997; Obermeier, 2009; Sims, 2012). Consequently, those of the Thorold Formation are interpreted as seismites. The next section describes similarly deformed laterally extensive facies from other stratigraphic horizons in Southern Ontario which are also interpreted as the product of co-seismic ground shaking.

3.4 SEISMITES IN RELATED ORDOVICIAN AND SILURIAN CLASTIC STRATA OF SOUTHERN ONTARIO

The field survey identified other distinct horizons composed of soft-sediment deformation structures including ball-and-pillow structures and contorted bedding within the Upper Ordovician Georgian Bay Formation and the Lower Silurian Grimsby and DeCew Formations (Table 3.1). The Upper Ordovician Georgian Bay Formation is a relatively thick (up to 250 m) succession of grey to blue-grey shales interbedded with sharp-based storm deposited sandstones (tempestites; Kerr and Eyles, 1991). Strata include numerous well-preserved sedimentary structures including graded beds, tool marks, gutter casts, scour and fill structures as well as current- and wave-formed cross-ripple lamination (Kerr and Eyles, 1991; Johnson et al., 1992). Small-scale loading structures are common, indicating rapid emplacement of sand on a muddy substrate during storms. Shale interbeds up to 1 m thick
record a return to fair-weather conditions (Fig 3.7C). At the Credit River in Mississauga a prominent horizon of well-developed ball-and-pillowed sandstone beds with sandstone pillows up to 1.5 m in diameter outcrop across a length of over 100 m (Figs. 3.2, 3.3, 3.7C, and 3.14A). The two deformed beds, separated by about 1 m of interbedded sandstones and shales, are overlain and underlain by flat-lying undeformed strata. Pillow bases are smoothly rounded to sub-rounded with some severely contorted pillows in the lower bed (Fig. 3.14B). Pillow structures are flat-topped suggesting that deformation took place near the sediment-water interface (see Pope et al., 1997). While storm-related loading structures are common in the Georgian Bay Formation, these structures are unusual by reference to their large size and spatial extent. The Credit River outcrop exposes over 8 m of flat-lying undeformed interbedded sandstones and shales that overlay the two deformed beds. Many of the overlying sharp sandstone beds are thicker (and therefore of greater load) than those of the ball-and-pillow beds. It is significant that no deformation is seen higher up the strata as would typically be seen with storm influenced load structures (Fig. 7C; Brenchley and Newall, 1977; Perez-Lopez and Perez-Valera, 2012) suggesting that simple bulk loading and storm influences were not the cause of the ball-and-pillow deformation. Deformed tool marks on the bases of pillows suggest that deformation did not occur immediately following deposition suggesting that a sudden trigger was required to cause the deformation of the sands beds and subsequent foundering into the underlying and less dense mud.

Distinctive red colored shale and sandstones of the Grimsby Formation were deposited in a peritidal to shoreface environment representing the final phase of delta progradation in what is now Southern Ontario from the Taconic Mountains (Johnson et al., 1992; Brett et al., 1995; McLaughlin and Brett, 2006). Outcrops of ball-and-pillow sandstone
structures are prominently displayed in the Lower Silurian Grimsby Formation at several locations across the study area from Clappison’s Corners to the Niagara Gorge, New York (Table 3.1; Figs. 3.2 and 3.3). As with the Georgian Bay Formation, associated sedimentary structures include ripple marks, hummocky cross-stratification, mud cracks, sole markings and gutter casts typical of a storm influenced setting (Kilgour and Liberty, 1981; Brett et al., 1995). Rounded and contorted sandstone pillows up to 1 m in diameter are exposed in outcrop at Clappison’s Corners and the Niagara Gorge. Sandstone pillows are surrounded by a structureless mudstone with vertical diapirs separating individual pillows (Figs. 3. 7D and 3.15AB). Deformed tool marks underlying the base of pillows imply deformation took place subsequent to loading suggesting a triggering event other than simple loading by storm waves (see McLaughlin and Brett, 2006).

Elsewhere along the Niagara Peninsula and Western New York State, the Lower Silurian DeCew Formation displays prominently exposed beds of severely contorted and folded dolostone especially along outcrops in the Niagara Gorge (Brett, 1982; Brett et al., 1990; Brett et al., 1995; Middleton et al., 2009; Table 3.1; Fig. 3.2). The DeCew Formation is a dark grey, thin and medium to massive bedded, dolomite-rich dolostone recording a range of depositional sub-environments in a fluvially to storm-influenced shallow marine setting and is frequently cross-stratified and ripple laminated (Kilgour and Liberty, 1981; Johnson et al., 1992; Brett et al., 1995). An extensive and representative outcrop of deformed DeCew Formation dolostone facies occurs along the New York side of the Niagara Gorge between Lewiston and the Whirlpool (Figs. 3.2, 3.7EF, and 3.16AB). A 3 m thick section displays a single bed of highly-contorted and extensively deformed hummocky cross-stratification and dark gray shales. Strata are tightly folded into numerous small pillows with numerous water
escape structures indicative of a rapid triggering event. These facies were interpreted as seismites based on their wide regional distribution (Brett et al., 1990; McLaughlin and Brett, 2006) and this model is supported here.

3.5 DISCUSSION

Seismically-deformed sandstone and dolostone described here from Southern Ontario can be favourably compared with many other earthquake-deformed sediments that are widely reported from Middle Ordovician to Carboniferous strata across Ohio, Kentucky and Virginia. These take the form of ball-and-pillows and contorted bedding very similar to those structures described here (Greb and Dever, 2002; Onasch and Kahle, 2002; Jewell and Ettenson, 2004). Other geographically-extensive and correlative horizons of Upper Ordovician ball-and-pillows have been described (Pope et al., 1997) along the distal margins of the Appalachian foreland basin and were attributed to large earthquakes (>M6) associated with uplift of the Cincinnati Arch. Other extensively distributed deformation structures found within Upper Ordovician limestone and shale in Kentucky suggest that seismic shaking at times was an important influence on epicontinental sedimentation; some work has related co-seismic deformation to specific basement fault zones (Jewell and Ettenson, 2004). In this regard, co-seismic deformation structures in laminated carbonate facies from the mid-Silurian Eramosa Member (Guelph Formation) of the Bruce Peninsula were described in a previous paper (Chapter 2). Intraformational faults and thin breccia horizons in ‘varve-like’ dolostones result from episodic debris flow (debrizes) interpreted as seismites generated by a large earthquake of (>M7) disturbing an area of more than 130 km² of the then sea floor. Deformation was related to reactivation of a specific basement structure, in
that case, the Grenville Front Tectonic Zone a major first-order Precambrian structure within
the Canadian Shield. The relationship between seismicity and particular basement structures
in Southern Ontario is discussed further below.

As a general rule, a large volume of work shows that earthquake shaking sufficient to
induce liquefaction, loading and ball-and-pillow structures can only be produced by
earthquakes equivalent to or larger than M5.25 to 5.5 (Allen, 1986; Ambraseys, 1988;
Moretti et al., 1999; Kahle, 2002). It can therefore be assumed that all of the seismites
identified here and elsewhere in mid-continent were generated by ground shaking by a
moderate earthquake of at least magnitude M5. Furthermore, while earthquake epicenters for
the events identified in Southern Ontario are unknown, the correlation between the
geographic extent of liquefaction features and earthquake magnitudes can be used to estimate
size of paleo-earthquakes (Table 3.2; Allen, 1986; Ambrasays, 1988; Fig. 3.17). For
example, an earthquake of at least M6 is required to generate liquefaction features across the
5 km lateral extent of the ball-and-pillow structures in the Thorold Formation and a minimum
earthquake of M7 to generate the liquefaction features within the Grimsby Formation which
are distributed over a lateral distance of 75 km. McLaughlin and Brett (2006) suggest the
seismically-deformed DeCew horizon extends over an area of at least 200,000 km². If the
DeCew deformation is representative of a single correlative seismic event then a very large
regional earthquake of at least M8 is suggested.
3.5.1 Relationship of paleo-seismicity to basement structures in the study area

The Hamilton and Niagara Peninsula study area lies directly above and close to several major Precambrian structures. In this regard, the western Lake Ontario region is characterized by persistent seismicity especially along the Toronto-Hamilton Seismic Zone (Wallach et al., 1998; Fig. 3.18). The study area lies close to several major regional Precambrian crustal structures and is within 150 km of the Grenville Front Tectonic Zone to the west and within 50 km of the Central Metasedimentary Belt Boundary Zone (CMBBZ) to the east and which extends beneath Lake Ontario and the Niagara Peninsula as the seismically-active Niagara-Pickering Linear Zone (NPLZ). Several other deep structural lineaments all converge on the study area and are also related to modern seismicity (Mohajer, 1993, Thomas et al. 1993; Wallach et al., 1998; Figs. 3.18). Some, such as the Hamilton-Lake Erie lineament (HLEL) which trends south-southwestward to the north shore of Lake Erie, have been linked with faulting of Upper Middle Ordovician strata (Wallach et al., 1998; Fig. 3.18). The Dundas Valley, a deep re-entrant valley that cuts through the Niagara Escarpment near Hamilton, is aligned with the northeastward-southwestward trending Hamilton-Presq’ile Lineament (HPEL) of Wallach et al. (1998) suggesting a structural control on bedrock topography. The location of the Niagara Gorge (and its predecessor the buried St. David’s Gorge) may also be structurally controlled (see Eyles et al., 1993). Many other structures can be inferred from the presence of distinct aeromagnetic lineaments and other geophysical anomalies but their geology is not well known. In summary, the Niagara-Hamilton study area is structurally complex and it is not an unreasonable hypothesis that these were active during subsidence of the Appalachian basin as noted elsewhere in adjacent parts of the U.S.
The data presented here on seismites in Lower Paleozoic strata cannot easily be used to identify any specific basement structure in the western Lake Ontario region; the available information is too coarse spatially. Deformation within the Thorold Formation appears to be absent at the southern and western portions of the study area, therefore a relationship with the GFTZ may be ruled out and is more likely related to structures within the Hamilton-western Lake Ontario area. Seismicity may also be related to the Algonquin Arch a major forebulge in the underlying Precambrian related to Appalachian basin subsidence (Sanford et al., 1985; Brett et al., 1998; Ettensohn and Brett, 2002; Ettensohn, 2008). Seismically-shaken shoreface strata described here were deposited along the southern edge of the Algonquin Arch at the outer margin of the Appalachian basin which experienced rapid subsidence during the Upper Ordovician through the mid-Silurian (i.e., coeval with deposition of Georgian Bay, Thorold, Grimsby and DeCew strata described here; Sanford et al. 1985). Here it can be noted that mid-Upper Ordovician to mid-Silurian seismites from a distal foreland basin setting very similar to Southern Ontario have been linked to recurring uplift of the Cincinnati Arch in the U.S. (Onasch and Kahle, 1991, 2002) where it has been estimated that recurrence intervals for large earthquakes (>M6) were of the order of every 2 to 4 million years. More frequent smaller earthquakes may have been persistent and more frequent throughout the Upper Ordovician to Silurian interval (Pope et. al, 1997). An earthquake-related interpretation is supported by previous investigations of the regional structural setting of Southern Ontario during the Ordovician-Silurian. Sanford (1993) showed that block faulting, uplift and arching was a common process in what is now Southern Ontario (Fig. 3.19) during that time span and which he related to several episodes of far-field stresses from late stage Taconic and Acadian orogenies. This resulted in the re-activation of Precambrian basement structures and block
faulting of overlying Paleozoic strata at different times. Several of these basement structures are seismically active at the present day in response either to ongoing tectonic stresses accompanying plate movement and/or postglacial rebound (Wallach et al., 1998). In summary, much evidence suggests the importance of synsedimentary structural adjustments and earthquake activity within a mid-continent intracratonic setting. Seismites reported here are the sedimentary records of co-seismic shaking along the coastal margin of the Appalachian basin.

Finally, outcrop field data presented here describing several hitherto unrecognized Lower Paleozoic seismites from the western end of Lake Ontario and Niagara Peninsula area combined with evidence of late glacial seismic activity and ongoing modern seismicity near Precambrian structures (Chapter 4) support the current model for mid-plate seismicity involving reactivation of brittle basement (Daneshfar and Benn, 2002; Bartholomew and Van Arsdale, 2012).

3.6 CONCLUSIONS

A systematic field and drill core survey of Early Paleozoic strata was completed in Southern Ontario, Canada with the purpose of identifying the sedimentary and structural record of past earthquakes during subsidence of the Appalachian Basin during the Lower Ordovician to Upper Silurian interval. Examination focused on siliciclastic and dolostone shoreface strata (Georgian Bay, Thorold, Grimsby, DeCew) composed of alternating sandstone and shale interbeds which are particularly susceptible to liquefaction and loading during severe ground shaking. The survey was conducted in the western Lake Ontario and Niagara Peninsula area which is heavily populated and is underlain by complexly structured Precambrian basement
associated with modern day seismicity. The survey shows that synsedimentary seismicity and
ground shaking of shoreface sediments is recorded by laterally extensive horizons of large
‘ball-and-pillow’ sandstones (up to 2 m in diameter and 5 km in lateral extent along outcrop)
that foundered into underlying shale. These are interpreted as seismites that record recurring
earthquakes of at least M6 coeval with rapid subsidence of the Appalachian basin and uplift
of the nearby Algonquin Arch. Deformation cannot be ascribed to any specific basement
structure but results of this study suggest a long Phanerozoic history of basement reactivation
which continues to the present day.
### Table 3.1: Outcrops of “potential seismites” in Southern Ontario.

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Locality Description</th>
<th>Formation</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Claremont Access – Niagara Escarpment, Hamilton, Ontario</td>
<td>Ball-and-pillow horizons</td>
<td>Thorold</td>
</tr>
<tr>
<td>2</td>
<td>Upper Jolley Cut Access – Niagara Escarpment, Hamilton, Ontario</td>
<td>Ball-and-pillow horizons</td>
<td>Thorold</td>
</tr>
<tr>
<td>3</td>
<td>Sherman Access – Niagara Escarpment, Hamilton, Ontario</td>
<td>Ball-and-pillow horizons</td>
<td>Thorold</td>
</tr>
<tr>
<td>4</td>
<td>Kenilworth Access – Niagara Escarpment, Hamilton, Ontario</td>
<td>Ball-and-pillow horizons</td>
<td>Thorold</td>
</tr>
<tr>
<td>5</td>
<td>Credit River at Eglinton Avenue Bridge, Mississauga, Ontario</td>
<td>Multiple ball-and-pillow horizons</td>
<td>Georgian Bay</td>
</tr>
<tr>
<td>6</td>
<td>Clappison’s Corners, Ontario – roadcut east side of Highway No. 6</td>
<td>Ball-and-pillow outcrop</td>
<td>Grimsby</td>
</tr>
<tr>
<td>7</td>
<td>Niagara Gorge – Art Park trail, Lewiston, New York</td>
<td>Ball-and-pillow outcrop</td>
<td>Grimsby</td>
</tr>
<tr>
<td>8</td>
<td>Devil’s Hole State Park, Niagara Falls, New York</td>
<td>Horizon of convoluted bedding</td>
<td>DeCew</td>
</tr>
<tr>
<td>9</td>
<td>DeCew Falls, Thorold, Ontario</td>
<td>Horizon of convoluted bedding</td>
<td>DeCew</td>
</tr>
<tr>
<td>10</td>
<td>Burleigh Hill Road, Thorold, ON</td>
<td>Outcrop of convoluted bedding</td>
<td>DeCew</td>
</tr>
</tbody>
</table>

Refer to Figure 3.2 for site locations.
<table>
<thead>
<tr>
<th>Formation</th>
<th>Age</th>
<th>Estimate of Minimum Epicentral Distance</th>
<th>Estimated Minimum Earthquake Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Georgian Bay</td>
<td>Upper Ordovician</td>
<td>100 m (unknown)</td>
<td>M5</td>
</tr>
<tr>
<td>Grimsby</td>
<td>Lower Silurian</td>
<td>35 km</td>
<td>M7</td>
</tr>
<tr>
<td>Thorold</td>
<td>Lower Silurian</td>
<td>5 km</td>
<td>M6</td>
</tr>
<tr>
<td>DeCew</td>
<td>Lower Silurian</td>
<td>250 km*</td>
<td>M8</td>
</tr>
</tbody>
</table>

*after McLaughlin and Brett (2006) estimate of geographic extent of deformation over 200,000 km²*
Figure 3.1. Major tectonic elements and structures of Southern Ontario. CMBBZ – Central Metasedimentary Belt Boundary Zone. GFTZ-Grenville Front Tectonic Zone; CMBBZ-Central Metasedimentary Belt Boundary Zone. Hashed rectangle indicates study area (after Armstrong and Carter, 2010 and Boyce and Morris, 2002 and references therein).
Figure 3.2 Study area and key plan.
Figure 3.3  Outcrop and core locations within Georgian Bay, Grimsby, Thorold, and DeCew Formations. Drill cores for Thorold Formation (did not display seismic related deformation structures).
Figure 3.4  Ordovician and Silurian stratigraphy of Southern Ontario indicating Formations displaying seismsites. Stratigraphy after Armstrong and Carter (2010).
Figure 3.5  Location of ball-and-pillow horizons in the Thorold Formation, Hamilton. Ball-and-pillow exposure locations ref. Table 3.1 (1- Claremont Access, 2- Jolley Cut, 3- Sherman Access, 4- Kenilworth Access).
Figure 3.6. Outcrops of ball-and-pillow structures in the Thorold Formation, Hamilton. A: Claremont Access, B: The Jolley Cut, C: Sherman Access, D: Kenilworth Access.
Figure 3.7  Stratigraphic logs of selected outcrops. A. Thorold Fm. (The Jolley Cut – Site 2), B: Thorold Fm. (Sherman Access – Site 3), C: Georgian Bay Fm. (Credit River, Mississauga – Site 5), D: Grimsby Fm (Clappison’s Corners – Site 6), E: DeCew Fm. (Robert Moses Power Station Access Road – Site 8), F: DeCew Fm (Devil’s Hole State Park – Site 8). (Site numbers refer to Table 3.1 and Fig. 3.2).
Figure 3.7 DEF
Figure 3.8  Sandstone pillow structures. A: Claremont Access, B: The Jolley Cut, C: Sherman Access, D: Kenilworth Access.
Figure 3.9  Deformed shale/mudstone within ball-and-pillow horizons. A: mudstone wrapping sandstone pillow (Jolley Cut). B: upward intrusion of mudstone between sandstone pillows (Sherman Access).
Figure 3.10  Contorted laminae within sandstone pillow structure (The Jolley Cut).
Figure 3.11  Orientations of long axes of pillow structures (Sherman Access).
Figure 3.12  Progressive detachment and deformation of load structures; (a) denser sand layer, (b) underlying mud (after Owen, 2003). With continued ground shaking denser sand pillows founder within underlying mud matrix. Not to scale.
Figure 3.13  Deformation by simulated “earthquake shaking” of laminated bed of sand sinking into muds. Displaying stages (A-E) of laminated bed of sand sinking down into a less dense mud disturbed by simulation of ground shaking. Mud flows around sand pillows as they sink (from Kuenen, 1957).
Figure 3.14  Ball-and-pillow horizons within Georgian Bay Formation, Credit River, Mississauga. A: Deformation horizons. B: Distorted sandstone pillow displaying deformed tool marks.
Figure 3.15  Grimsby Formation ball-and-pillow structures. A: Clappison’s Corners, ON (measuring stick 1 m long). B: Art Park, Lewiston, N.Y.
Figure 3.16  DeCew Formation contorted and convoluted bedding. A: Devil’s Hole State Park, Niagara, N.Y. B: Burleigh Hill Side Road, St. Catharine’s.
Figure 3.17  Relationship of earthquake magnitudes and epicentral area (after Allen, 1986; Ambrasays, 1988 and Pope, 1997; and references therein).
Figure 3.18. Aeromagnetic and gravity lineaments in Southern Ontario including the Bruce Peninsula area including earthquake epicentres (after Boyce and Morris, 2002; Doughty et al., 2014; and references therein). Relationship of earthquake magnitudes and epicentral area (after Allen, 1986; Ambrasays, 1988; Pope et al., 1997 and references therein). GFTZ: Grenville Front Tectonic Zone; CMBBZ: Central Metasedimentary Belt Boundary Zone; NPLZ: Niagara-Pickering Linear Zone; HLEL: Hamilton-Lake Erie Lineament; HPL: Hamilton-Presqu’ile Lineament; GBLZ: Georgian Bay Linear Zone.
Figure 3.19  Schematic geological sections in the vicinity of Buckhorn Lake in south-central Ontario (modified from Sanford, 1993). Faulting of Paleozoic strata indicates reactivation of Precambrian structures. Location of sections is indicated on inset map.
REFERENCES


CHAPTER 4:
LAKE SEDIMENTS AS NATURAL SEISMOGRAPHS: EARTHQUAKE-RELATED (SEISMITES) IN CENTRAL CANADIAN LAKES

ABSTRACT

Central Canada experiences numerous intraplate earthquakes but their recurrence and source areas remain obscure due to shortness of the instrumental and historic records. Unconsolidated fine-grained sediments in lake basins are ‘natural seismographs’ with the potential to record ancient earthquakes during the last 10,000 years since the retreat of the Laurentide Ice Sheet. Many lake basins are cut into bedrock and are structurally-controlled by the same Precambrian basement structures (shear zones, terrane boundaries and other lineaments) implicated as the source of ongoing mid-plate earthquake activity. This paper highlights results of a multi-year seismic sub-bottom survey of lakes Gull, Muskoka, Joseph, Rousseau, Ontario, Wanapitei, Fairbanks, Vermilion, Nipissing, Lake Huron, Georgian Bay, Mazinaw, Simcoe, Timiskaming, Kipawa, Parry Sound and Lake of Bays, encompassing a total of more than 2000 kilometres of high-resolution track line data supplemented by multibeam and sidescan sonar survey records.

All studied basins show a consistent sub-bottom stratigraphy of relatively-thick lowermost lateglacial facies composed of interbedded semi-transparent mass flow facies (debrites, slumps) and rhythmically-laminated (varved) silty clays. Mass flows together with cratered (‘kettled’) lake floors and associated deformations reflect a dynamic ice-contact glaciolacustrine environment. Exceptionally thick mass flow successions in Lake Timiskaming, along the floor of the Ottawa-Timiskaming Graben within the seismically-active Western Quebec Seismic Zone, point to a higher frequency of earthquakes and slope
failure during deglaciation and rapid glacio-isostatic rebound though faulting continues into the postglacial. Lateglacial faulting, diapiric deformation and slumping of coeval lateglacial sediments is observed in Parry Sound, Lake Muskoka and Lake Joseph, which are all located above prominent Precambrian terrane boundaries. Lateglacial sediments are sharply overlain by relatively thin rhythmically-laminated and often semi-transparent postglacial silty-clay laminations. A marked unconformity between the successions records dramatic reductions in water depths under a dry climate from c. 9,000 and 8,000 ybp when the Laurentian Great Lakes were disconnected. Buried horizons of in situ tree stumps recording these low water conditions are newly identified by sub-bottom profiling in Parry Sound. Postglacial neotectonic activity is recorded by faults, slumps and debris flows in Lake Simcoe (above a terrane boundary) and especially within lakes Timiskaming and Kipawa, recording ongoing deformation within the Western Quebec Seismic Zone along the Ottawa-Timiskaming Graben. High resolution seismo-stratigraphic data presented here support the model that ongoing mid-plate earthquake activity is a consequence of brittle deformation of the upper crust of the North American plate. Such activity appears to have been greatest during deglaciation but continues today.
4.1 INTRODUCTION

Until quite recently, the Canadian Shield and offlapping Paleozoic platforms in mid-continent North America were thought to have been tectonically stable for many millions of years and thus of low seismic risk. As seismic networks have expanded there is growing recognition of frequent intraplate seismic activity (see Adams and Basham, 1989; Wallach et al., 1998; Tremblay et al., 2003; Dineva et al., 2004, 2007; Kim et al., 2006; Mereu et al., 2013). New seismic events occurring in unexpected locations reveal ‘weak points’ in the North American plate associated with active crustal deformation (Mazzotti, 2007). It is now widely appreciated that eastern mid-continent North America experiences many small to moderate magnitude intracratonic earthquakes that are a threat to infrastructure both onshore and along the offshore continental margin (Stein and Mazzotti, 2007). Recent large earthquakes in Canada include the Timiskaming Earthquake of 1935 (M6.2) which was felt over an area of 2.5 million km², and the 1944 (M.5.8) Cornwall Earthquake which to date is Canada’s costliest in terms of damage to infrastructure (approximately $2 million – 1944 dollars; Bent, 1996). Mohajer (1997) estimated a major (M7) earthquake can be considered ‘credible’ in the heavily populated southern Ontario-Quebec corridor; a recent report for the Insurance Bureau of Canada by AIR Worldwide (2013) concluded that the risk of such an earthquake is 1:500 and is estimated to create $61 billion of damage to infrastructure of which only $12 billion is currently insured. Expected ground motions are modelled to exceed the design limits for nuclear generating facilities at Pickering and Darlington along the northern shore of Lake Ontario near Toronto. The instrumental record is sparse for many areas of mid-continent and AIR Worldwide (2013) also identified that current Canadian
seismic risk maps on which building codes are based are outdated and do not include recent
data.

Against a backdrop of increased risk, the origin of mid-plate seismicity is not yet well
understood but appears to be related to the reactivation of Precambrian structures often
deeply buried below Phanerozoic strata. These structures record major phases of plate
tectonic activity involving crustal accretion and rifting along the eastern North American
continental margin over the last billion years (Eyles et al., 1993; Boyce and Morris, 2002;
Tremblay et al., 2003; Bartholomew and Van Arsdale, 2012; Cox et al., 2012). Of particular
concern in eastern central North America is the Western Quebec Seismic Zone (WQSZ;
Forsyth, 1981) a belt of enhanced seismic activity that extends from Canada into the
coterminous US and poses a regional risk to mines, critical nuclear facilities and the large
urban areas of New York, Montreal and Ottawa (Fig. 4.1). In the case of the nation’s capital
and Montreal, seismic risk is compounded by the presence of soft glaciomarine sediments
(Leda Clays) and aged infrastructure (Motazedian and Hunter, 2008; Rosset and Chouinard,
2008). The Val-des-Bois Earthquake (M.5.0) of 2010 caused the strongest shaking ever
measured in the city of Ottawa (Natural Resources Canada, 2013). Geomorphic evidence of
large (M>7) earthquakes at 7060 years before present (ybp) and 4550 ybp occurs close by in
the form of landslides in Leda Clays within the Ottawa Valley (Aylesworth et al., 2000;
Aylesworth, 2007).

There are many practical difficulties and data gaps to be faced in fully understanding
mid-plate seismicity and underlying controls on earthquakes and causal mechanisms have
been said to be ‘elusive’ as yet (Bartholomew and Van Arsdale, 2012). The major challenge
is that many Precambrian structures are not exposed at surface but are hidden below thick
Paleozoic strata and Pleistocene glacial sediments. As a consequence, correlation of mapped epicentres with the poorly-defined subcrops of Precambrian structures is not straightforward, as emphasized by Adams (1992), Wallach et al. (1998) and Dineva et al. (2004). Another major impediment to understanding of earthquake risk is that the historic record of earthquake activity only began relatively recently in the early seventeenth century and the instrumental record is also of very short duration (typically <75 years) complicating efforts to determine recurrence intervals for moderate to large events. The lack of a detailed network of recording instruments across such a large area is another problem; regions once considered to be of low seismicity often simply reflect an absence of data (Mazzotti, 2007). A further area of debate is whether mid-plate seismicity in the glaciated portion of North America is principally related to continuing glacio-isostatic rebound and thus can be expected to decrease in the future, or reflects persistent ongoing movement of the North American plate (Ma et al., 2008). A similar debate is occurring in northwest Europe (Morner, 2011).

Given the lack of any lengthy historic record in eastern North America, emphasis has been placed since the pioneering work of Shilts (1984) on examining the geologic and geomorphic record of seismic activity focussing on the sub-bottom stratigraphy of postglacial lakes and other waterbodies (e.g., Shilts and Clague, 1992; Kelson et al., 1996; Ouellet, 1997; Aylesworth et al., 2000; Talwani and Schaeffer, 2001; Tuttle, 2001; Aylesworth, 2007; Cauchon-Voyer et al., 2008; Doughty et al., 2010a, 2013;). The eastern mid-continent North America is particularly suited to this approach given the widespread and dense distribution of lakes across the region. The present paper describes the results of an investigation of sixteen lakes in Ontario and Quebec and represents a significant contribution to a growing data set.
on the use of lake sediments as ‘natural seismographs’ in mid-continent North America (e.g., Moernaut et al., 2009; Strasser et al., 2013).

4.2 STUDY AREA AND OBJECTIVES OF THIS PAPER

This study presents the results of one of the largest surveys of the sub-bottom stratigraphy of lake basins conducted anywhere in eastern North America to date. It encompasses 16 lake basins across an area of approximately 100,000 km² extending from Sudbury in the north, south to Toronto, and from Lake Huron in the west to Timiskaming and Kipawa in western Quebec adjacent to the border with Ontario (Figs. 4.1, 4.2, 4.3A-C). The study area includes the southernmost part of the exposed Canadian Shield which consists of Precambrian strata, and the adjacent Ontario-Erie lowlands where Precambrian basement and associated structures are buried under Lower Paleozoic platformal sedimentary strata that thicken southwards towards the Michigan and Appalachian basins. The lakes reported in this paper were selected because of their proximity to prominent mid-Proterozoic basement structures such as terrane boundaries, rifts, and less well understood geophysical lineaments and shear zones (Figs. 4.2, 4.3A).

This paper commences by briefly describing the geological evolution and resulting bedrock structure of eastern North America and its relation to mid-continent seismicity using a new compilation of historic (post 1627 AD) earthquake epicentres. It then reviews and synthesizes more than 2000 line kilometres of high-resolution sub-bottom seismo-stratigraphic data from 16 lake basins with the principal objective of identifying areas of co-seismic deformations in lake sediments and their geographic location relative to underlying Precambrian structures.
4.3 SEISMICITY AND REGIONAL STRUCTURE IN EASTERN NORTH AMERICA

A regional compilation of earthquake epicentres reveals a strong geographic relationship with the broad scale tectonic subdivision of eastern North America (Fig. 4.1). Earthquake epicentres for Ontario, western Quebec and the northeastern United States for events of M2.5 or greater were retrieved from the Geological Survey of Canada’s (GSC) Canadian Earthquake Epicentre File (CEEF) and includes events recorded from 1626 through 2013. The northeastern United States earthquake epicentre and magnitude data was retrieved from the National Center for Earthquake Research (NCEER) catalogue for the central and eastern United States and includes seismic events from 1627 through 2010 (United States Geological Survey, 2010). Epicentre locations plotted prior to 1930 have an uncertainty of at least +/- 50 km (Halchuk, 2009) and those for 1970-1991 have an uncertainty of about 10 km (Stevens, 1994).

As related above, the emerging consensus is that mid-plate seismicity is related to reactivation of older Precambrian structures (Eyles et al., 1993; Wallach et al., 1998; Dineva et al., 2004, 2007; Cox et al., 2012). This model is supported by data presented on Figures 4.1 and 4.3 despite some uncertainty of the precise location of historic epicentres. While a comprehensive review of the geological history is not possible here, broadly parallel northeast-trending belts of epicentres identify the successive positions of the North American continental margin during the formation and breakup of the supercontinents Rodinia from 1.5 to 1.0 billion years before present (Ga ybp), and Pangea, (from 450 to 350 Ma ybp) both times when large areas of crust were accreted to or detached from the margin. The Grenville Front Tectonic Zone is a wide suture zone marking the approximate continental boundary of
North America at c. 1.5 Ga (Fig. 4.1) when South American crust (Grenville Province; GP) was added to North America during the Grenville Orogeny. The subsequent breakup of Rodinia between 750 to 600 Ma ybp is recorded by a northeast trending boundary some 200 km to the east marking the margin of the Iapetus Ocean (Iapetan Rifted Margin; Fig. 4.1). Eastward, the Appalachian Front records the inland limit of compressional deformation associated with the building of Pangea after 440 Ma ybp when African crust was accreted to North America and in turn, this is paired with an outermost Atlantic Rifted margin formed by Mesozoic breakup of Pangea during the Late Triassic at c. 220 Ma ybp (Fig. 4.1).

It is very noticeable that the regional distribution of earthquake epicentres mirrors the broad structure of eastern North America outlined above, in particular the two parallel belts marking the Iapetus and Atlantic rifted margins (Fig. 4.1). The Iapetus margin underlies the modern St. Lawrence River and is reflected in a clustering of numerous epicentres along the so-called St. Lawrence Rift System within what is known as the Western Quebec Seismic Zone (WQSZ) (Kumarapelli and Saull, 1966; Duchesne, 2007; see below; Tremblay et al., 2003). The WQSZ shows two distinct but still poorly understood clusters (herein called ‘sub-zones’) that form crudely oriented northwest-trending belts separated by a zone of lower activity. The westernmost sub-zone directly underlies the Ottawa-Timiskaming Graben and lakes Timiskaming and Kipawa (Fig. 4.3A) extending west along the Ottawa and Timiskaming Grabens into Northern Ontario and east into the US along the Hudson Valley as far as New York City. The largest population centres in eastern North America lie within these two belts underscoring the need to understand intraplate seismicity.

The regional geology of the Canadian Shield within the study area in Ontario and Quebec consists of a complex mosaic of terranes within the Grenville Province (Fig. 4.2)
produced by prolonged obduction during the Grenville Orogeny. The Grenville Front Tectonic Zone (GFTZ) forms a prominent structural feature under Lake Huron and emerges on land just south of Sudbury where it abuts Mesoproterozoic and Archean rocks to the north. It was active at several times in the early Paleozoic and produced seismites in carbonate and clastic sedimentary facies of the Michigan Basin (McLaughlin and Brett, 2006; this thesis Chapters 2 and 3). The Grenville Province is subdivided into the Central Gneiss Belt (CGB) to the west and the Central Metasedimentary Belt (CMB) to the east separated by the Central Metasedimentary Belt Boundary Zone (CMBBZ) which passes southward under Pickering Nuclear Generating Station on the north shore of Lake Ontario (Fig. 4.2). Each belt is subdivided further into component terranes such as the Go Home, Muskoka, Bancroft, Harvey-Cardiff Arch (or domain), Belmont, Grimsthorpe, Mazinaw, Sharbot Lake and the complex Frontenac-Adirondack Belt (Easton, 1992). To the west, in Georgian Bay, the Parry Sound Shear Zone lies along the border of the Shawanaga and Parry Sound terranes and underlies the glacially overdeepened basin now occupied by Parry Sound (Fig. 4.2). In their evaluation of seismic source zones Bartholomew and Van Arsdale (2012) also highlighted the additional importance of post-orogenic extensional faults formed at the conclusion of the Grenville Orogeny. These are expressed as NW-SE oriented extension fractures and faults associated with a ‘basin and range’ topography that developed across the study area after 1 Ga ybp. Such fractures may explain the strikingly linear form to the eastern shoreline of Lake Huron which is associated with the seismically active Georgian Bay Linear Zone of Wallach et al. (1998; Fig. 4.3A). These authors presented a detailed review of seismicity in southern Ontario and identified several seismically active basement lineaments
that converge in a distinct cluster at the western end of Lake Ontario basin, the most populated area in Canada.

4.3.1 Structural controls on topography

The geomorphological record of faulting and reactivation of basement structures is widespread in the study area especially along the northern boundary of Paleozoic cover rocks within the Canadian Shield. The Shield is a low relief (< 100 m) undulating peneplain dominated by Precambrian bedrock and expressed morphologically as an undulating knobbly terrain with many lake basins. This surface is the product of deep differential weathering during the Mesozoic and Tertiary followed by uplift and stripping of soft weathered regolith. Final removal of weathered material was accomplished within the last 2 million years by Pleistocene ice sheets resulting in the exposure and glacial scour of fresh unweathered rock. Regolith has rarely been preserved below later glacial fills (Dyke, 2004). Weathering and glacial erosion were deepest along fractures and faults such that the Shield is geomorphologically a ‘glacially-scoured etch plain’ with a very pronounced structural control on its topography and the location of the many hundreds of lake basins on the Shield surface. Evidence of Phanerozoic basement reactivation in the study area is provided by the very close association between modern day topography cut by rivers and glaciers on top of Paleozoic strata and underlying Precambrian basement. Many lakes occupy bedrock basins that are fault controlled by underlying Paleozoic strata (Sanford, 1993; Fig. 4.4). Faulting occurred during a succession of Appalachian orogenies (c. 440 to 350 Ma years ago) associated with the assembly of Pangea. Seismic activity at this time triggered seismites in unconsolidated sea floor carbonate and clastic sediments in the form of large ‘pillowed’
sandstones, faults and debrites that record liquefaction of sediment, loading into disturbed mud as a consequence of reverse density gradients, and mass flow activity (this thesis Chapters 2 and 3). Subsequently, much of the eastern part of the study area underwent uplift, unroofing Paleozoic strata and crustal stretching during the breakup of Pangea and the opening of the North Atlantic (c. 220 Ma years ago). As related above, the largest structural feature produced at this time was the St. Lawrence Rift System, a large failed rift that underlies the modern St. Lawrence River valley (Cauchon-Voyer et al., 2008; Kumarapelli and Saull, 1966; Fig. 4.1). In addition to a close structural control on the location of lake basins, the regional drainage patterns, even in areas of thick glacial cover, are controlled by neotectonic jointing which affects all strata regardless of age. Maximum regional horizontal stress is consistently clustered around a NNE to E direction and regional mapping shows a consistent grouping of joint orientations into NE-SW and NW-SE trending sets in both Paleozoic and Precambrian rocks (see Lam et al., 2007; Eyles and Scheidegger, 1999, 1995; Andjelkovic et al., 1998; Eyles et al., 1997).

4.4 GLACIAL HISTORY OF STUDY AREA

The study area was glaciated many times during the Pleistocene but a lacustrine sedimentary record only exists for the final phases of the last (Wisconsin) glaciation. The area was entirely covered by the Laurentide Ice Sheet which reached its maximum thickness and extent in mid-continent at about 20,000 ybp (Dyke, 2004). Lacustrine sediments containing warm-to-cool climate indicators spanning the last interglacial through mid-Wisconsin glaciation are preserved in buried bedrock valleys at Toronto but to date these have not been
identified in any modern lake basin and are presumed to have been eroded elsewhere. Lake basins were apparently cleaned out to bedrock by glacial erosion and backfilled during deglaciation.

The Shield is, in general, lacking in sediment cover; exposed glacially-scoured bedrock predominates with patches of lake sediments left by large deglacial lakes (see below). Glacial sediments up to 100 m thick, thicken southwards onto Paleozoic strata and bedrock is only exposed in the deeper valleys. Deglaciation began in the south about 12,000 ybp and cleared the most northern parts of the study area at Timiskaming by about 9,000 ybp (Fig. 4.5). Very large high-level lakes formed against the retreating ice margin such as glacial Lake Algonquin in the Huron basin, glacial Lake Iroquois in the Ontario basin, and Barlow-Ojibway along the length of the Timiskaming Graben (Jackson et al., 2000). Lake levels fell abruptly in the early postglacial as water drained through the ice free, but still glacioisostatically depressed, Ottawa and St. Lawrence valleys (Fig. 4.5). There is emerging evidence that the Laurentian Great Lakes were disconnected shortly thereafter and lake levels were lowered by as much as 60 m below modern levels as a consequence of a warm dry climate in mid-continent just after 9,000 ybp (McCarthy and McAndrews, 2012). Large areas of the floors of the modern lakes Erie, Huron and Ontario were exposed at this time recorded by brackish closed basin conditions, and greatly diminished outflows along the Niagara River. Lake levels have risen subsequently, as recorded by drowned beach systems and flooded archaeological sites, as a consequence of cooler and wetter climates and regional tilting associated with enhanced glacio-isostatic uplift of the outlet of the Great Lakes at the eastern end of Lake Ontario (see Jackson et al., 2000, and Jacobi et al., 2007 for additional details).
4.5 **GEOPHYSICAL METHODS**

The high resolution ‘chirp’ seismic reflection survey data described here was collected using an EdgeTech high resolution XStar or 3200-XS digital sub-bottom profiling system (see EdgeTech, 1998 and 2009) with a SB 216S tow vehicle (‘fish’). The system transmits an FM sonar ‘chirp’ pulse created by linear sweeping over the frequency range of 2-12 kHz for 20 ms (see Eyles et al. 2003). Sediment and water depths displayed on the seismic stratigraphic profiles assume a constant velocity of 1450 m/s (e.g., Doughty et al., 2013, 2010a; Cauchon-Voyer et al., 2008; Strasser et al., 2007; Mullins and Eyles, 1996). Water depth data determined from seismic data agree with charting by the Canadian Hydrographic Survey.

Track line density is sufficient in some cases (Parry Sound, Lake of Bays, Timiskaming and Joseph) to allow seismo-acoustic fence diagrams to be constructed. Vehicle positioning was recorded from standard Garmin-GPS instruments. XStar data were streamed to either external JAZZ-type removable hard disks or to DAT, both in XStar SEGY format (a modification of the standard SEGY format; Barry et al., 1975; EdgeTech, 1998). After transferral to a separate workstation, data processing steps included: translation to standard SEGY format; partitioning into appropriate track-lines/lengths; conversion of coordinates from minutes-of-arc (i.e., latitude/longitude) to UTM; correction of coordinates due to GPS tracking errors; conversion of coordinates from points-to-line for incorporation into a GIS; conversion into Seismic Unix SEGY format (Cohen and Stockwell, 2012) for visualization and any further processing. In addition, the envelop amplitude was calculated for each seismic/track-line resulting, generally, in improved imagery. Most conversions, when error-free, occurred within a batch framework (consisting of various conversion scripts). 3200-XS data are collected and stored directly by the field unit as EdgeTech JSF formatted files.
Similar data processing steps (to the XStar, above) were applied with the addition of a JSF-to-SEGY conversion. Seismic/sub-bottom imagery was also derived directly using the standard 3200-XS software package.

4.6 LACUSTRINE FACIES TYPES AND SUCCESSIONS

Seismic profiling of sediments preserved on lake floors using the XStar system provides excellent high-resolution seismo-stratigraphic data typically to a maximum sub-bottom depth of ~ 60 m in fine-grained silty clay sediments (Figs. 4.6 – 4.22). This depth window allows full penetration of the entire thickness of the sedimentary fill of most lakes down to bedrock with the exception of Lake Timiskaming where the base of the Pleistocene sediments is too deep to be resolved. Acoustic penetration in more coarse-grained lake floors (i.e., sand, bedrock) is typically less than 5 m.

Most of the lakes investigated are characterised by an undulating bedrock basement of moderate to high relief, often sufficient to protrude through the entire sediment cover and isolate sediments into sub basins separated by bedrock highs devoid of any sediment. Bedrock forms a hard ‘acoustic basement’ that is evident on many seismic profiles. Notably, no primary glacial sediments such as till or glaciofluvial outwash gravels or any glacial landforms such as moraine ridges have been observed on seismic profiles. This confirms the model that lake basins were essentially swept clean by ice and that deglaciation was rapid and not punctuated by still stands and deposition of coarse grained primary glacial sediment. Instead, bedrock basins only became active depocentres for relatively fine sediment as the ice margin withdrew in contact with deep lateglacial lakes.
4.6.1 Lake sub-bottom stratigraphy

Two superposed acoustic stratigraphic successions can be identified in lakes across the study area forming a consistent bipartite bottom stratigraphy (Figs. 4.6 – 4.22). The presence of a stratigraphic couplet that records lateglacial and postglacial phases of sedimentation was first recognized by Shilts (1984) and was confirmed by subsequent work (e.g., Lazorek et al., 2006; Eyles et al., 2003; Moore et al., 1994; Rea et al., 1994; Shilts and Clague, 1992, and references therein). These two successions are expressed on seismic profiles as a lowermost, darker-coloured, more reflective succession resting on bedrock (designated LG for late glacial; e.g., Fig. 4.6) and characterized by closely-spaced, high-frequency parallel reflectors typical of rhythmically-laminated glaciolacustrine silty-clays deposited during deglaciation in proglacial (ice-contact) lakes. In contrast, an upper thinner (typically less than 5 m) and largely semi-transparent seismic succession (designated PG for post glacial; Figs. 4.6, 4.7, 4.8) shows much weaker acoustic returns and very closely-spaced parallel reflectors typical of modern annually-deposited postglacial sediments dominated by organic material, typically silica-rich gyttja derived from diatoms (Lazorek et al., 2006; Shilts and Clague, 1992).

Weaker acoustic returns in the postglacial succession are the consequence of much reduced rates of clastic minerogenic sedimentation compared to those during deglaciation; many lake basins surrounded by bare rock devoid of sediment are consequently ‘sediment starved.’ Exceptionally, the postglacial succession in the northern part of Lake Timiskaming is on average between 15-20 m thick and up to 40 m adjacent to the mouths of the large rivers that rework exposed lateglacial lake sediments in the surrounding basin. Modern sedimentation rates in Lake Timiskaming are as high as 0.5 cm/yr\(^{-1}\) (Doughty et al., 2013; Shilts, 1984).
While the existence of a bipartite acoustic sedimentary succession in glaciated Shield lakes in Canada is well established, new significance is now placed on the climatic significance of the unconformity that commonly separates them. This erosion surface truncates underlying lateglacial facies (e.g., Fig. 4.9) and is the consequence of abrupt falls in lake levels across the region when large glacial lakes impounded against the retreating Laurentide Ice Sheet suddenly drained (Fig. 4.5). Coring and dating of the unconformity in lakes Nipissing and Huron suggests that the unconformity also records a lengthy 1000 year-long episode of dry climate shortly after deglaciation between c. 9,000 and 8,000 ybp when runoff was drastically reduced throughout the Great Lakes basin and closed basin conditions obtained (McCarthy et al., 2012; Lewis et al., 2007). A dramatic expression of this event can be seen on seismic profiles of the stratigraphy below the floors of several protected inlets along the northern margin of Parry Sound (Fig. 4.3C, 4.9A). There the unconformity is well expressed as a dark, highly reflective zone some 5 m thick at the base of overlying Holocene sediments. This horizon occurs at a consistent elevation of some 50 m below modern lake levels and is characterised by numerous closely-spaced point source reflectors producing a distinctive ‘spotty’ seismofacies type that has not been seen in other lake basins. These seismofacies are typically associated with ice-rafted debris in fine lacustrine sediment but the size and number of point reflectors is atypical and forms extensive horizons. Instead, these facies are tentatively interpreted as the rooted stumps of sub fossil trees buried by lacustrine sediment during an increase in lake levels as climate cooled after 8,000 ybp.
4.6.2 Lateglacial debris flow

This study highlights the important role of debris flow during lateglacial sedimentation, hitherto unrecognized in existing models of glaciolacustrine sedimentation (Ashley, 1975). An important sedimentary process operating during lateglacial time in Canadian lake basins has been seasonally-active, density-driven underflows (quasi-continuous turbulent flows) and overflows resulting in accumulation of high-frequency rhythmically-laminated facies. These are likely of annual origin (‘varves’) but this cannot be positively demonstrated in the absence of cores from lake bottom sediments. However, Antevs (1925) studied exposed outcrops of lateglacial lacustrine sediments in the northern part of the study area and demonstrated an annual control on sedimentation. Of considerable interest here is the common presence in lateglacial successions of thickly-bedded ‘chaotic-massive-to-stratified’ beds (‘c-m-s facies’). These are seen as distinct transparent to weakly reflective intervals within lateglacial successions of high-frequency, rhythmically-laminated glaciolacustrine silty-clay (Figs. 4.6, 4.8, 4.9). ‘C-m-s’ facies have undulating lower bounding surfaces which are conformable or erosional. In the latter case, these units are chaotic consisting of a mix of darker and lighter coloured zones interpreted as rafts of underlying laminated facies. Upper surfaces are frequently hummocky in form. Chaotic seismic facies pass laterally and vertically into massive transparent facies that, in turn, are overlain by high-frequency rhythmically-laminated facies marking a return to rhythmic sedimentation (Figs. 4.8, 4.9). The upper surface of c-m-s beds is frequently hummocky and beds thicken downslope. ‘C-m-s’ beds are readily interpreted as sediment gravity flow facies, specifically those formed by debris flow (debrites) based on their description from cores in other basins (Strasser et al.,
Basal chaotic facies within erosionally-based ‘c-m-s’ beds are interpreted as relatively proximal facies resulting from slumping and incomplete downslope mixing of masses of semi-coherent unconsolidated rhythmically-laminated facies. A hummocky surface to such flows is consistent with downslope compressional thickening during flow (e.g., Joanne et al., 2013). Water escape structures (seen as narrow vertical pillars; e.g., Fig. 4.8) are very common indicating the development of overpressured conditions in such deposits.

Massive facies (mainly transparent signatures) are interpreted as the more completely homogenised (‘fully mixed’) and further-travelled portion of debris flows. The same seismo-facies were identified on high resolution seismic records from Seneca Lake, the largest and deepest of the New York Finger Lakes by Halfman and Herrick (1998). Limited outcrop work to date has recognized downslope mass flow deposits in the form of slumps and massive, apparently disorganized sand beds (see Kelly and Martini, 1986; Kaszycki, 1985). This study shows that massive facies are a volumetrically significant part of the lateglacial fill of lake basins. Hitherto, the extent of mass flow activity in lake basins during deglaciation has not generally been recognised (see Shilts et al., 1992) largely because of the relatively limited seismic data available (Shilts and Clague, 1992).

Unfortunately modern outcrops through lateglacial deposits containing mass flow facies are rare as these are usually covered by slumped colluvium. Figure 4.10 shows disturbed near-surface horizons of lateglacial glacial Lake Barlow-Ojibway silty-clay laminations briefly exposed by road construction near Ville Marie on the eastern side of Lake Timiskaming in Quebec. This outcrop is considered significant because Antevs (1925, p. 81) presented a detailed description of outcrops of the same lateglacial age in the nearby Ville
Marie-Bearn area that contain a very prominent intraformational deformation horizon. This regionally correlative horizon was described as being ‘many feet’ thick, faulted, tilted, and contorted with intraformational rafts and blocks of undisturbed ‘varves’ lying stratigraphically directly above his ‘varve 498’. This deformed horizon fulfills one of the most important criteria for recognition of co-seismic origin of soft sediment deformation, namely widespread distribution. It can be suggested that Antevs (1925) was reporting a thick debrite bed produced by co-seismic slumping similar to that seen on sub-bottom seismic profiles of Barlow-Ojibway deposits below the floor of Lake Timiskaming (Figs. 4.6, 4.7). The presence in seismic data of what are interpreted as large rafts of laminated silty clays in these facies (Fig. 4.8) agrees with the outcrop observations of Antevs (1925). Unfortunately, the Barlow-Ojibway deposits are too extensively disturbed by faulting below the floor of Lake Timiskaming (see Doughty et al., 2013) to allow meaningful determination of the stratigraphic frequency and down basin extent of such beds. Nonetheless, they are a very common component of the basin fill and are thick and extensive indicating repeated large scale mass flow events during deglaciation. In this regard, it is highly significant that examination of Antevs (1925) detailed descriptions of many other outcrops throughout the Timiskaming district (pp. 105-115; Antevs, 1925) reveals the common presence of faults and slumped horizons within ‘varved’ deposits (which he often attributed to glacial activity such as iceberg scour) together with unusually thick (1.5 m) beds he attributed to sudden inputs of meltwater (the so-called ‘drainage varves’ of Antevs, 1925). Given the seismicity of the Timiskaming Graben these structures are suggestive of repeated co-seismic deformation involving faulting and debris flow. Adams (1982, 1989) suggested that a record of earthquake activity is preserved as deformed horizons in the laminated successions of the
Timiskaming basin; geophysical data presented here, together with the previous observations of Antevs (1925), provide strong support for this hypothesis and suggest that further work is warranted. Debrites are very common in other lakes of the study area (Figs. 4.8, 4.11) but it is significant that the thickest and most spatially extensive occur below Lake Timiskaming within the seismically-active Western Quebec Seismic Zone.

Subaqueous debris flows are triggered by many processes in dynamic ice-contact glaciolacustrine environments such as the melt of buried ice (see below), ice berg calving and scouring, meltwater flood events, sudden lake drainage or depositional oversteepening, and of course by earthquakes. The debris flows found in the lateglacial record of Lake Timiskaming, within sediments deposited in glacial Lake Barlow-Ojibway (Figs. 4.6, 4.7), are unusually thick (~ 5 m) and extensive (2 km) suggesting earthquake-triggered slumping akin to the modern slumps seen along the lake’s margins and in nearby Lake Kipawa (see below; Doughty et al., 2013). This appears likely, but cannot at this stage, be demonstrated. Moernaut et al (2007) and Strasser et al (2013, 2007) describe similar earthquake-triggered mass flows from other large lakes comparable in thickness and extent to those described here.

4.6.3 Lateglacial faulting and diapirism related to possible earthquake activity

In addition to subaqueous slumping and mass flow triggered by seismic activity, the present study identifies several other examples of lateglacial deformations (faults and diapirs) that are clearly unrelated to the melt of buried ice or slumping on the floors of Lake Nipissing, Parry Sound, Lake Muskoka and Lake Joseph. These structures lie directly above
Precambrian terrane boundaries (Figs. 4.8, 4.9B, 4.11, 4.12C) and can be convincingly related to seismic activity during deglaciation. The structures are restricted to lateglacial sediments and are truncated by the unconformity forming the base of the overlying postglacial acoustic succession (Figs. 4.8, 4.9). This provides a precise constraint on the timing of faulting because lateglacial deposits were formed during a fairly restricted time window during the brief (~ 500 year) lifetimes of large glacial lakes that formed along the ice front during deglaciation and suggests that faulting in such instances may be a consequence of rapid postglacial rebound and structural reactivation immediately after deglaciation.

Lateglacial faulting is especially pronounced below the floor of Lake Nipissing where numerous faults are truncated by the modern lake floor which is an erosion surface (Figs. 4.12C, 4.13) cut by the drainage of glacial Lake Algonquin. Lake Nipissing occupies a broad fault-bounded morphotectonic depression which forms an arm of the Ottawa Graben which is seismically active at the present day and which continues northwards as the Timiskaming Graben (Fig. 4.2). Elsewhere, faulting of lateglacial sediment, the vertical escape of gas/water and large-scale diapiric movement of water-saturated sediment is seen below a thin cover of postglacial sediments where Lake Joseph empties into Lake Rosseau (Fig. 4.12B). Step-like extensional faulting occurs over some 2 km length of the lake floor giving rise to marked offsets of correlative horizons within the lateglacial stratigraphy (Fig. 4.9C). These structures are associated at depth on seismic records by narrow tapered ‘pillars’ of massive unstructured facies typically produced by upward escape of fluid or gas (Fig. 4.9C). Larger scale upward movement of sediment toward the lake floor is also seen in the form of a diapiric ‘mushroom-like’ structure (Figs. 4.12A,B). A thin debris flow with a distinctly hummocky surface extends downslope toward this structure. Diapirs associated with pits and
linear troughs on the lake floor and produced by erosion of sediments by escaping fluids or
gas were also noted above terrane boundaries in western Lake Simcoe by Boyce et al. (2002).

### 4.6.4 Lateglacial deformation related to melt of buried ice

Many of the studied lakes contain deformed sediments resulting from the melt of buried
 glacier ice trapped along lake floors. Several lake basins, especially Lake of Bays, Gull, Mazinaw and part of Timiskaming, show areas of their floors that are dimpled (‘kettled’ or cratered) as a consequence of the melt of large remnant ice blocks buried under a cover of lateglacial sediment. Ice melt resulted in the collapse of overlying and adjacent sediment and the production of a crater (Fig. 4.13) - a product of the deglaciation of a strongly undulating often high relief bedrock surface. Large remnant ice blocks were severed from the downwasting and retreating margin of the Laurentide Ice sheet by bedrock highs protruding through the ice. This ice was trapped in the confined topographically lowermost parts of narrow lake basins and weighted down by lacustrine sediment (Fig. 4.14; see Eyles et al., 2003). Some ice blocks may have originated as stranded icebergs. These craters (‘kettle basins’) are characterised on acoustic profiles by rings of faulted and chaotically-bedded sediment where any original stratigraphy has been disrupted by collapse and slumping (e.g., Eyles et al., 2003; Kaszycki, 1987; Klassen and Shilts, 1982).

The rate of postglacial sedimentation has generally been insufficient (with the exception of Lake Timiskaming) to entirely fill these collapsed sub-basins which are still expressed as circular depressions in the bathymetry of the lakes. Kaszycki (1985) described the effects of thawing buried ice on glaciolacustrine sediments exposed in outcrop within the
Gull River watershed, including Gull Lake itself, and suggested that all major lakes in that watershed are floored by intensely faulted laminated sand, silt and clay as a result of ice trapping and melt.

4.7 POSTGLACIAL FAULTING AND SLUMPING

Seismic data from many of the lake basins investigated in this study are also interpreted to show evidence of postglacial (Holocene) faulting and slumping that may relate to earthquake activity. Detailed seismic data from the bottom stratigraphy of Lake Timiskaming has already been presented (Doughty et al., 2013) and a single illustration is presented here of faults that affect the entire lateglacial and postglacial Holocene fill of this lake (Fig. 4.7). Open fractures on the lake floor and numerous slumps around the basin margin in deep water (Figs. 4.15, 4.16) also testify to ongoing deformation related to frequent earthquakes within the Western Quebec Seismic Zone (see below).

Recent slumps on the floor of Lake Kipawa were mapped by Doughty et al (2010a) and their geographic distribution was shown to be systematically related to the epicentral location of the 1935 M6.2 Timiskaming Earthquake. Figure 4.15 shows a map of slumps and other lake floor features in Lake Timiskaming compiled from multibeam, acoustic and side scan datasets. The Lake Timiskaming basin consists of a long linear basin with a flat marginal ‘shelf’ of varying width in shallow water (0 to 15m depth). The shelf has a sharply-defined outer edge that overlooks a steep, scarp-like slope that descends to deeper water (generally, 140 to 160m depth; a maximum of 198m has been recorded). The shelf results from planation of lateglacial glaciolacustrine sediments by wave-induced current activity in
shallow water. Shelf width is greatest on the eastern side of the basin (varying between 600 and approximately 2000m at the north end of the lake, Fig. 4.15A) and narrowest or non-existent on the west along the exposed bedrock trace of the West Shore Fault (varying between 0 and a maximum of 600m; Fig. 4.15A). The eastern slope is distinctly ‘crenulated’ with numerous semi-enclosed bowl-shaped excavations and narrow gullies along the shelf edge. Debris flow lobes are common on the lower slope and in many cases extend from the mouths of upslope bowl-shaped valleys (Figs. 4.15A, 4.15B). This suggests the importance of mass flow in the headward erosion of such valleys; indeed their abrupt headward termination is similar to the so-called ‘theatre-headed’ canyons of semi-arid areas where back wall retreat is accomplished as a consequence of spring sapping, undercutting of back walls and their collapse. Spring sapping as a major causative agent is likely for the crenulated form of the shelf break in Lake Timiskaming and is suggested by the form of a large ‘A’-shape depression present on the outer shelf edge in Paulson Bay (Fig. 4.17; see also Shilts, 1984). This feature consists of two narrow linear gullies that join together at their headward ends leaving a remnant high-standing block of sediment between; small enclosed depressions to the south link the two gullies (forming a crossbar as in the letter ‘A’) and separate another remnant block to the south. This area of the lake floor is crossed by two sub bottom track lines and the location of gullies can be seen to be controlled by faults and diapirs in underlying lateglacial glaciolacustrine sediments (Fig. 4.18). Subsidence and sediment collapse over growing faults is suggested by a small enclosed depression to the north. Linear open fissures are clearly observed on nearby multi-beam and side scan profiles (Fig. 4.19). This suggests an actively-developing lake floor geomorphology where collapse
of sediment is occurring above linear fractures or faults that control fluid migration through lacustrine sediments and subsequent seepage zones on the lake floor.

The data presented above seem to indicate that groundwater seepage and spring-sapping of soft glaciolacustrine sediment is a widespread subaqueous process operating along the outer shelf edge and slope of the Lake Timiskaming basin, at least at its northern end (Fig. 4.15A; Kotilainen and Hutri, 2004; Jensen et al., 2002; LaFleur, 1999; Shilts and Clague, 1992; Shilts, 1984). Soft overpressured sediment is prone to mass wasting and explains the common presence of debris flow lobes on the lower slopes of bowl-shaped depressions. Overpressuring of sediment and upward movement of saturated postglacial sediment is indicated by the diapiric structures that immediately underlie gullies in Paulson Bay (Fig. 4.18). Given the known seismicity of the area and presence of earthquake-triggered slumps in nearby Lake Kipawa (Doughty et al., 2010a) it is reasonable to argue that many debris flows have been triggered by coseismic ground shaking and slumping of glaciolacustrine sediment softened by groundwater seepage (Shilts, 1984). Doig (1991) reported deformed silty clay sediments in short (< 1m) gravity cores collected from a single site in northern Lake Timiskaming that were interpreted as the product of earthquake-triggered mass flow during the 1935 (M6.2) Timiskaming Earthquake. The present study, which focuses on basin-wide seismic data, reveals the much broader geographic extent of debris flows on the lake floor. Debris flows are as much as 5 m thick on acoustic profiles and the largest lobe covers some 400,000 m² of the lake floor (Fig. 4.16).

It is highly significant that recent debris flows are mainly present on the lake floor north of the Montreal River Fault which is the southernmost active fault in the Timiskaming Basin. Thick lateglacial sediments are present south of this fault but evidence of faulting or
mass flow activity on the lake floor is lacking (Doughty et al., 2013) and indicates that the
southern part of the Timiskaming basin is structurally stable. Furthermore, the distinct
preferential geographic distribution of debris flows on the east side of the lake as a whole
(Fig. 4.15) suggests some directionality in seismic wave propagation or may simply indicate
that the Timiskaming East Shore Fault (TESF) is more active than its western counterpart.
This latter suggestion is strongly supported by onshore geomorphic evidence seen on the
floor of the graben north of Lake Timiskaming. Between New Liskeard and Earlton a 20 km
long and strikingly linear 8m high bluff located directly above the northward continuation of
the TESF has been interpreted as the consequence of postglacial faulting along TESF and
displacement of lateglacial deposits of lake Barlow-Ojibway (Doughty et al., 2013, 2010b). If
correct this is the first recorded example of a fault scarp resulting from earthquake activity in
central Canada; a program of land-based seismic data acquisition is currently in progress.

Figure 4.20A shows the preliminary results of a lake-based magnetic survey of
Kempenfelt Bay in Lake Simcoe (Fig. 4.2). Magnetic mapping reported briefly by Boyce et
al. (2002) identifies a number of west-east trending curvilinear anomalies and a broad zone
(approximately 3 km in width) of high amplitude northwest-trending magnetic anomalies that
crosses the middle section of the bay. The high-amplitude anomalies mark the boundaries of
the Alliston-Go Home basement shear zone in the underlying Precambrian basement and
reflect the presence of mylonitic rocks along the shear zone that have much higher
susceptibility than the surrounding basement gneisses. The magnetic image also shows
clearly that the shear zone is offset by a west-east magnetic lineament. The lineament is
interpreted as the trace of a strike-slip basement fault that offsets the boundary with a left-
lateral displacement of about 500 m (Fig. 4.20).
Side-scan sonar imaging of Kempenfelt Bay shows that the southeastern boundary of the faulted shear is associated with slumping of Holocene sediments on the adjacent basin slope (Fig. 4.21). Discordant outcrop patterns imaged on the slope indicate the presence of several large, rotated slump blocks. The slump blocks appear to be part of a larger, lobate mass flow deposit that extends onto the basin floor. The debris flow lobe is expressed on bathymetric data as a distinct bulge in bathymetry contours at the southeastern edge of the shear zone (Fig. 4.20B). Large-scale slump features were not identified elsewhere along the basin margins. The features are interpreted as evidence for Holocene slumping triggered by neotectonic reactivation of underlying basement structures (see also Boyce et al., 2002; Boyce and Morris, 2002).

Sub-bottom sonar profiles from Kempenfelt Bay show that west-east basement magnetic trends are associated with zones of normal faulting and also localized thrust faulting of the postglacial lacustrine infill (Figs. 4.21-4.22). Normal faults comprise graben-like block faults that strike parallel or sub-parallel to the basin axis (Fig. 4.21A); these were noted by Todd and Lewis (1993). Reverse faults occur as small ‘en echelon’ sets of west-east striking thrusts that show small vertical displacements (< 2 m) (Fig. 4.22B). Other features captured on sub-bottom profiles include gas escape structures that appear as characteristic convex-upward ‘bee-hive’ reflection patterns (Fig. 4.22A). The structures are associated with localized depressions and linear troughs in the lake floor that are produced by erosion of sediments by escaping gas (‘pock marks’). The markedly linear alignment of the trough-like features suggests that gases and pore waters are likely moving vertically along discrete fractures or faults in lake sediments (Boyce et al., 2002).
4.8 DISCUSSION

This study is based on a partial survey of the many hundreds of lakes in Ontario and western Quebec but it is an important first step in an ongoing regional assessment of seismic risk using lacustrine records. It confirms the utility of using such sediments as natural seismographs and shows that the lacustrine fill of several water bodies (Parry Sound and lakes Timiskaming, Joseph, Muskoka and Nipissing) record deformation interpreted to relate to ground shaking during lateglacial earthquakes; all of these basins are structurally-controlled and lie directly above major Precambrian basement structures (Fig. 4.23). These deformations (faults, slumps, debris flows, water escape structures) can be collectively referred to as *seismites*. Those in Lake Nipissing (Figs. 4.12C, 4.13), Parry Sound (Fig. 4.9A), Lake Joseph (Fig. 4.8B) and Lake Muskoka (Figs. 4.8C, 4.11) are of lateglacial age (they are truncated by an early postglacial unconformity) and suggest the occurrence of moderate to large earthquakes during deglaciation and rapid crustal rebound. Those deformations in the Muskoka lakes occur above Precambrian terrane boundaries in the Canadian Shield directly along the margin of the Go Home and Muskoka terranes; those deformations in the Parry Sound area lie very close to the intersection of the Georgian Bay Linear Zone and Parry Sound Shear Zone (see Wallach et al., 1998; Figs. 4.2, 4.20).

Deformations identified in Lake Simcoe, Lake Timiskaming and Kipawa are, in contrast, of postglacial age as they affect both lateglacial and postglacial sediments. Those at Timiskaming and Kipawa are readily related to ongoing seismicity within the WQSZ associated with known measurable crustal deformation within the North American plate along the Timiskaming Graben (see Mazzotti, 2007). Postglacial deformations in Lake
Simcoe are likely related to activity along terrane boundaries that pass southward along the western margin of the lake and control the location of that margin (Figs. 4.2, 4.20).

In Lake Ontario, Thomas et al (1993) identified postglacial bedrock ‘pop-ups’ in the form of WNW trending elongate features projecting 1.5 to 2m above the lake floor from sidescan sonar data (see also Jacobi et al., 2007). In addition, so-called ‘plumose structures’, referring to a feather-like arrangement of small-scale ridges no more than 10-15cm in height, were mapped in postglacial sediment with a distinct ENE trend. Thomas et al (1993) considered these to be analogous to similar structures reported proximal to offshore ‘pockmarks’ on the eastern Canadian continental margin associated with active faults (e.g., Fader, 1991; Pecore and Fader, 1990). Thomas et al. (1993) also identified steeply-dipping scarps on the floor of southeastern Lake Ontario associated with apparent offsets of reflectors in glaciolacustrine clays. These were interpreted as normal faults with displacements of 10-15m but these so-called ‘offsets’ more likely reflect non-deposition of sediment on very steep bedrock slopes (‘bathymetric-controlled deposition’; see Doughty et al., 2013, p. 999).

Much discussion of earthquake risk has focussed hitherto on the seismically-active and regionally-prominent lithotectonic boundary between the Central Gneiss Belt and Central Metamorphic Belt (CMBBZ; Fig. 4.2) which passes southward below the Greater Toronto Area (population 5 million) and directly below the nuclear generating station at Pickering on the north shore of Lake Ontario. Faulted glacial sediments within 7 km of the plant were reported by Mohajer et al. (1992) but their origin remains elusive (see Eyles and Mohajer 2003; Godin et al., 2002) although some are considered to be neotectonic (Godin et al., 2002, p. 1389). Gull Lake lies directly above this structure to the north and although faulting is seen on acoustic profiles of lateglacial sediments, these are associated with craters
(kettles) and are, therefore, interpreted as a consequence of the melt of buried ice. Further work will focus on other lakes along different parts of the CMBBZ to more closely resolve the Holocene history of this complex boundary zone.

The introduction to this paper highlighted the challenge of discriminating earthquake-related deformations from non-seismic deformations produced by mass flow or glacial activity such as collapse over buried ice or glaciotectonic deformation. A major finding is that Shield lakes were cleared of any pre-existing sediment by the Laurentide Ice Sheet and only filled during deglaciation. As a consequence, deformation structures, resulting from glaciotectonic overriding of older sediments which complicates identification of co-seismic deformations, are absent from these basins unlike those preserved on land (see Eyles and Mohajer, 2003; Mohajer et al., 1992). This underscores the value of lake-based seismic risk studies.

This study also furthers understanding of the effects of geologically-recent mid-plate seismicity by specifically identifying the sub bottom geophysical characteristics of lacustrine deformation structures that are the result of non-seismic processes (e.g., 'kettles'; Fig. 4.13). It highlights, for example, the importance of mass flow during deglaciation. Widespread deformation in lateglacial lacustrine sediments is the product of deposition in highly dynamic proglacial lakes where rapid sedimentation, abrupt changes in lake depth and inflowing meltwater drainage, depositional oversteepening of fan delta slopes and melting of trapped and buried ice all result in deformation. In particular, the study shows that debris flow was a very common process in lateglacial waterbodies in contrast to previous models that emphasize a relatively simple annual control on sedimentation in front of retreating ice margins (Ashley, 1975). Only in the case of the seismically active Lake Timiskaming basin
can an earthquake-related origin be suggested on the basis of the unusual dimensions of debris flows in the lateglacial deposits of glacial Lake Barlow-Ojibway (Fig. 4.15).

The present paper supports the source model for intracratonic earthquakes presented by Bartholomew and Van Arsdale (2012). They suggest reactivation of faulted brittle upper crust has been localized to terrane boundaries and other poorly understood Precambrian basement fractures and lineaments (see also Wallach et al., 1998; Boyce et al., 2002; Boyce and Morris, 2002; Daneshfar and Benn, 2002). It follows that all Precambrian structures are potentially seismogenic. In this regard, the seminal study of Sanford et al. (1985) showed that significant faulting of Precambrian basement structures occurred in southern Ontario during Paleozoic orogenies (Figs. 4.3, 4.4); widespread congruence of topographic features such as valleys and lake basins cut into Paleozoic strata, that together with deeply buried Precambrian structures, indicate that basement reactivation and attendant fracturing and faulting of overlying strata has been a persistent feature of this part of mid-continent during much of the Phanerozoic (Eyles et al., 1993; Sanford, 1993). Modern drainage patterns cut into glacial sediments are controlled by neotectonic joints (Eyles and Scheidegger, 1995, 1999; Eyles et al., 1997) and stress-release buckles (‘pop ups’) on the surface bedding planes of Paleozoic strata are common (Jacobi et al., 2007). These various datasets point to an active neotectonic system in this part of the mid-continent with the potential for reactivation of deeply buried Precambrian structures close to major population centres. Future work will concentrate on lakes along the strikes of specific Precambrian structures such as the Central Metasedimentary Belt Boundary Zone which underlies the Pickering Nuclear Generating Station.
4.9 CONCLUSIONS

High resolution seismic reflection profile datasets were collected along more than 2000 km of track lines from a number of lakes across Ontario and western Quebec (Gull, Muskoka, Joseph, Rousseau, Ontario, Wanapitei, Fairbanks, Vermilion, Nipissing, Huron, Georgian Bay, Mazinaw, Simcoe, Timiskaming, Kipawa, Parry Sound, Lake of Bays), one of the largest such datasets collected to date in eastern North America. A wealth of acoustic data confirms that unconsolidated fine-grained sediments deposited in lakes during and after deglaciation about 10,000 ybp are ‘natural seismographs.’ Lake floor sediments record ancient earthquakes in the form of co-seismic faults, slumps, debris flows and diapiric water escape structures (collectively referred to as ‘seismites’) and, in addition, record the absence of seismic activity where such structures are not present (considered as ‘negative’ evidence; Strasser et al., 2013).

High resolution sub-bottom seismic records from five lakes (Nipissing, Parry Sound, Lake Muskoka and Lake Joseph) allow identification of lateglacial faulting and slumping likely related to ground shaking during earthquakes triggered by rapid crustal rebound immediately after deglaciation. These locations lie directly above Precambrian terrane boundaries. Lateglacial structures can be readily distinguished from those that affect younger Holocene sediments in lakes Timiskaming and Kipawa along the seismically-active Timiskaming Graben. This area forms part of the Western Quebec Seismic Zone that is associated with the St. Lawrence Rift System, a large failed rift which records ongoing persistent deformation within the North American plate. Deformation is ongoing along the floors of these lakes as indicated by faults, open crevices and recent slumps. Other
postglacial deformation structures such as slumps, faults and dewatering structures, which are most readily explained by reference to ground shaking during postglacial earthquakes, occur on the floor of Lake Simcoe, again directly above a Precambrian terrane boundary. Data on paleo-earthquakes presented in this paper supports the model that ongoing mid-plate earthquake activity in eastern North America is a consequence of brittle deformation of the fractured and faulted upper crust of the North American plate (Dineva et al., 2004; Mazzotti, 2007; Mereu et al., 2013). These structures are inherited from phases of obduction and rifting associated with the formation and breakup of the supercontinents Rodinia and Pangea. Compilation of regional earthquake epicentres in eastern North America confirms a distinct broad-scale association with major lineaments, suture zones and failed rifts recording the life histories of Rodinia and Pangea. Acoustic data presented in this paper from sixteen lakes indicate the importance of reactivated Precambrian terrane boundaries that are exposed at surface on the Shield and underlie many lake basins, but which southward become deeply buried under thick covers of Paleozoic and Pleistocene glacial sediments beneath the principal urban centres of eastern Canada. The precautionary principle suggests that all Precambrian structures in mid-continent North America must be considered potentially seismogenic. The enormous potential impact of mid-continent earthquakes on the economy of this heavily populated area (e.g., AIR Worldwide, 2013) makes further study a high priority and underscores the need for additional regional-scale geophysical investigations of natural lacustrine seismographs.
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Figure 4.1  Broad scale structure of eastern North America resulting from formation and breakup of Rodinia and Pangea with historic earthquake epicentres (1627 to 2013 AD) after Natural Resources Canada (2013) and Halchuk (2009). Major structural boundary locations were adapted from Bartholomew and Van Arsdale (2012), Boyce and Morris (2002), Carr et al. (2000), Mazzotti (2007), Thomas (2006) and Withjack et al. (2002). Direction of maximum regional compressive stress (for the study area) derived from Nuclear Waste Management Organization and AECOM Canada Ltd. (2011).
Figure 4.2  Terrane boundaries within the Grenville Province showing lakes where (potential) seismites have been identified in lateglacial or postglacial deposits (red stars). Lakes Nipissing, Timiskaming and Kipawa lie along prominent failed rift structures associated with the St.Lawrence Rift System (Fig. 4.1). Structural data summarized from Bartholomew and Van Arsdale (2012), Boyce and Morris (2002), Carr et al. (2000) and Mazzotti (2007).
Figure 4.3  (A) Study area. Studied lake basins (red stars) are indicated along with earthquake epicentres (Halchuk, 2009; Natural Resources Canada, 2013), faults, lineaments and terrane boundaries (Armstrong and Carter, 2010; Atomic Energy Control Board, 2000, Boyce and Morris, 2002; Carr et al., 2000; Daneshfar and Benn, 2002; McFall and Allum, 1989; Ontario Geological Survey, 2011; Sanford, 1993). (B) (C). Seismic data collection track lines for lakes shown in Figure 4.3A; lines used in this paper are highlighted in red and numbered.
Figure 4.3 B
Figure 4.3 C
Figure 4.4  Schematic geological sections in the vicinity of Buckhorn Lake in south-central Ontario (modified from Sanford, 1993). Faulting of Paleozoic strata indicates reactivation of Precambrian structures. Location of sections is indicated on inset map and on Figure 4.2 (along with the location of the Precambrian-Paleozoic contact, in bold).
Figure 4.5  Phases of late and postglacial lake development and marine incursions in Ontario after Jackson et al. (2000). Arrows indicate lake outflows.
Figure 4.6 (Next Page) Interpretation of seismic line 097 from Lake Timiskaming (see Figure 4.3B for location). Prominent debris flow deposits (debrites) occur within lateglacial Lake Barlow-Ojibway deposits. Panels are organized A-B-C, left-to-right (North-to-South). Panel B2 is an inset (close-up) from Panel B1. Shaded areas represent interpreted debris flows during the postglacial (PG – pink) and lateglacial (LG – blue).
Figure 4.6 (Continued)
Figure 4.7  Fence diagram of seismic facies in Lake Timiskaming showing broad extent of prominent debris flow facies seen as massive transparent beds (‘c-m-s facies’; see text for details) within lateglacial Lake Barlow-Ojibway deposits represented here as shaded units (refer to Fig. 4.6 for details). Refer to Fig. 4.3B for location for seismic lines.
Figure 4.8  (Next Page) Debris flow (features 1, 3 and 6) and fluid escape structures (5) in Lake Rosseau (A); debris flows (1-4 and 6) in Lake Joseph and Lake Muskoka (B, C); overpressuring of debris flow facies (6) and subsequent water escape structures (5) is commonly seen in many lakes such as in Lake of Bays (D). Refer to Fig. 4.6 for numeric code descriptions. Refer to Figs. 4.3B-C for location of seismic lines.
Figure 4.8 (Continued)
Figure 4.9  (A) Selected seismic profiles from: Parry Sound on Georgian Bay showing contact between lateglacial and postglacial sediment with horizons interpreted as stumps of trees (10) that grew at times of lowered lake level and were subsequently killed by rising water levels after 8000 ybp.  (B) Prominent erosional surface truncating lateglacial sediment in Lake Nipissing (7/8).  (C) Faulted lateglacial sediment in Lake Joseph (9) with fluid-escape structures (5). Refer to Figs. 4.3B, C for location of seismic lines and Figure 4.6 for numeric code descriptions.
Figure 4.10  Outcrop of folded and faulted glacial Lake Barlow-Ojibway silty-clays near Ville-Marie, Quebec (east of Lake Timiskaming; refer to Figure 4.2 for location). These sediments were probably deformed by co-seismic shaking. See text for details.
Figure 4.11  Seismic lines from Lake Muskoka showing debris flow features (1-4 and 6). Refer to Fig. 4.6 for numeric code descriptions. Refer to Figs. 4.3C for location of seismic lines.
Figure 4.12A  Fence diagram view of seismic facies in Lake Joseph showing extent of debris flow facies (shaded and 2, 3 – refer to Fig. 4.6 for numeric codes and colour descriptions) and vertical pipe-like structures (5; see also Fig. 4.12B for a detailed section, location indicated). Refer to Figs. 4.3B for location of seismic lines.
Figure 4.12B  Seismic lines showing fluid escape structures in lateglacial fill of Lake Joseph recorded by vertical pipe-like structures (5) where overpressured sediment has moved upward. Note correlative hummocky debris flow bed (4) at left suggesting mass flow and water escape were coeval events likely triggered by ground shaking. The lake lies directly above a Precambrian terrane boundary (Fig. 4.2).
Figure 4.12C  Seismic line from Lake Nipissing (see also Fig. 4.9B) showing faulted lateglacial sediments truncated by modern lake floor. The lake occupies the floor of a major Neoproterozoic rift basin associated with the Ottawa Graben and St. Lawrence Rift System (Figs. 4.2, 4.3).
Figure 4.13  Seismic lines illustrating craters (kettle holes, 11) on the floor of Lake of Bays (A) and Lake Mazinaw (B) resulting from melt of large ice blocks buried by sediment during deglaciation. Refer to Fig. 4.6 for numeric code descriptions. Refer to Fig. 4.3B for location of seismic lines.
Figure 4.14 (A) Bathymetry of Lake of Bays (A) and Lake Mazinaw (B; adapted from Eyles et al., 2003) showing prominent craters originating as kettle holes (Fig. 4.13). Bathymetric data collected using a dual-channel bottom sounder with line spacing of 10-50 m (fine to medium resolution) through to 100-150 m (coarse resolution) with crossing (tie) lines.
Figure 4.14B
Figure 4.15  (A-B) Multi-beam bathymetry of Lake Timiskaming showing distinctly crenellated form of slope around basin margin created by bowl-shaped slump scars (marked ‘S’) produced by spring sapping and mass wasting. Debris flow lobes extend basinward from mouths of slump scars (Fig. 4.16). Bathymetric data from Canadian Hydrographic Survey (2005).
Figure 4.15B
Figure 4.16  Debris flow lobes (outlined; imaged from multi-beam bathymetry) with hummocky upper surfaces at the foot of the eastern basin margin slope of Lake Timiskaming (see Figure 4.15 B1 for location). Debris flow activity was a common process during deglaciation of Ontario lakes (Figs. 4.8, 4.11) but the largest debris flow lobes identified to date occur in Lake Timiskaming (Fig. 4.6).
Figure 4.17  Bathymetric data showing gullies on floor of Paulson Bay in Lake Timiskaming resulting from spring sapping and collapse over faults. Seismic profiles (seismic track lines numbered and indicated by coarse lines) suggest upward movement of overpressured sediment below the area (Fig. 4.18). Note enclosed collapsed depression to the north directly over underlying fault. Refer to inset for location.
Figure 4.18  High resolution seismic profiles in Lake Timiskaming across area shown in Figure 4.17 showing pillars of deformed lateglacial sediment identified as diapirs; see Figure 8 for similar structures in Lake Rosseau. Refer to Figs. 4.3B and 4.17 for location of seismic lines and Fig. 4.6 for numeric code descriptions.
Figure 4.19  (A-C). Multi-beam images of open fractures on floor of Lake Timiskaming that lie directly above faults and which suggest ongoing neotectonic activity and structurally controlled subsidence. Location indicated on D. Enclosed depressions (marked ‘ED’ on C) similar to those depicted here are also seen on Fig. 4.17. Approximate look direction and position for A1-C1 is indicated (arrowed) on A2-C2. Features in A and B are approximately 1m in height. The enclosed depression in C is approximately 2m in depth with the scarp (to the east) approximately 10m high. Water depths vary between 15 and 30m.
Figure 4.20  (A) Total field magnetic map of Kempenfelt Bay in Lake Simcoe (Fig. 4.2). Northwest-trending linear anomaly marks boundary of Alliston-Go Home terrane in Precambrian basement. Boundary is offset by left-lateral slip of approximately 500 m on southwest-trending fault. (B) Bathymetric map of basin. Note debris flow lobe (arrowed) on southeastern margin of the shear zone. Adapted from Boyce and Pozza (2004) and Boyce et al. (2002).
Figure 4.21  (A) Sub-bottom sonar profile showing normal faulting of lake bottom Holocene muds and silts in Kempenfelt Bay. Graben is filled by undisturbed Holocene sediment. B: Side-scan sonar image of southern basin margin of Kempenfelt Bay, showing large rotated slump block of Holocene sediment (location of image shown in Fig. 4.20B) on the southeastern margin of the Alliston-Go Home shear zone. Slumping is interpreted as a co-seismic feature associated with basement fault reactivation. Adapted from Boyce et al (2002).
Figure 4.22  (A) Sub-bottom sonar profile across small sub-basin showing gas escape columns. Escape of gas (or pore water) produces small pits and linear trough-like features (inset) on lake floor. Troughs suggest movement of gases along fracture planes. (B) Sub-bottom profile showing ‘en echelon’ reverse faults in postglacial laminated sediments. Note rotation of fault blocks and small vertical offsets of bedding (1-2 m). Structures indicate compressional deformation of the lake-floor, possibly in association with strike-slip movements on basement faults identified in Figure 4.20B. Adapted from Boyce et al. (2002).
Figure 4.23 Location of postglacial and lateglacial seismite features identified in this study with major Precambrian tectonic boundaries (grey lines) and earthquake epicentres (pink circles). Seismogenic deformation structures reported: (1) Todd and Lewis, (1993) and Boyce et al (2000); (2-4) Thomas et al. (1993); (3) Jacobi et al (2007); (5) Eyles (2013), unpublished) are also shown.
REFERENCES


5.1 SUMMARY

Southern Ontario experiences recurring low to moderate magnitude intraplate earthquakes linked to reactivation of poorly-understood Precambrian basement structures. The heavily populated region supports much vulnerable infrastructure, such as ageing nuclear facilities that overlies complexly structured basement. This raises serious concerns in the heavily populated region regarding the level of seismic risk posed by these intraplate earthquakes in an area of poorly understood risk. The objective of this thesis was to systematically assess the geologic record of paleoseismicity in Southern Ontario to test the hypothesis that intraplate seismicity is the consequence of brittle failure of the upper crust and reactivation of pre-existing Precambrian structures. The aim was to identify potential seismogenic structures and thus contribute to refinement of seismic hazard estimates for the region.

5.1.1 Paleozoic seismicity

Field investigations across the central Bruce Peninsula, supplemented by drill core and thin section analysis, confirmed that deformation structures displayed within the mid-Silurian Eramosa Member of the Guelph Formation are seismites. The unique rhythmically-laminated dolostones of the Marble Unit exhibit syndepositional thrust faults associated with two unusual intraformational horizons of clast breccia and folded bedding. Deformation was
generated by ground shaking that caused resedimentation and mass flow events across the then sea floor of the Michigan basin. Seismites covering an area of some 130 km² were generated by an earthquake of at least M7. Deformation is located within 50 km of the Grenville Front Tectonic Zone (GFTZ), a major crustal boundary. Seismicity was associated with tectonic compression within an otherwise passive intracratonic setting. It is highly significant that these structures are broadly correlative with other seismites documented within the Michigan basin in Michigan and Ohio linked to the reactivation of the GFTZ and rapid basin subsidence (see Onasch and Kahle, 1991; 2002).

A systematic survey of Appalachian basin deposits of Lower Paleozoic shoreface siliciclastic sediments (Ordovician-Silurian) within the western Lake Ontario and Niagara regions identified seismites along the Niagara Escarpment in the Hamilton area. Field investigation confirmed that a 5 km exposure of ball-and-pillow structures within the Lower Silurian Thorold Formation is the product of rapid foundering of sand into underlying muds liquefied by ground shaking. The seismites identified here record an earthquake of at least a magnitude M6 across the margin of the developing foreland basin. Other seismites in the form of ball-and-pillows and severely contorted and convoluted bedding within the Upper Ordovician Georgian Bay Formation and the Lower Silurian Grimsby and DeCew Formations suggest that a number of earthquakes (M5 to M9) affected a large swath of the western Lake Ontario and Niagara Peninsula. Deformation structures are similar to other seismites reported of this age in New York, Ohio, Kentucky and Virginia attributed to reactivation of Precambrian basement structures and rapid subsidence of the Appalachian basin accompanied by uplift of the Cincinnati Arch (see Pope et al., 1997; Jewell and Ettensohn, 2004; McLaughlin and Brett, 2006).
Together these two studies (Chapters 2 and 3) greatly expand the known geologic record of paleoseismicity documenting seismites within strata deposited over a lengthy period of 20-25 million years. Seismites are documented from the Upper Ordovician through the mid-Silurian across both the Michigan and Appalachian basins. Distribution is geographically extensive, produced by earthquakes generated by far-field stresses from sequences of Appalachian orogenies coinciding with rapid basin subsidence and uplift of the Algonquin Arch. Strata was deformed syndepositionally within both carbonate and siliciclastic marine sediments deposited in a wide variety of depositional environments ranging from quiet water lagoons to storm-influenced shoreface environments. Seismites across the central Bruce Peninsula are attributed to reactivation of the Grenville Front Tectonic Zone during the mid-Silurian; however, data within the Appalachian basin was considered too coarse to attribute to a specific structure in the complexly structured western Lake Ontario region.

This work documents, for the first time, seismites within the Michigan basin of Southern Ontario and expands upon the work of Onasch and Kahle (1991; 2002) describing broadly correlative and similar strata in Michigan and Ohio some 500 km to the south. Field investigation of siliciclastic Upper Ordovician through Lower Silurian strata of the Appalachian basin builds upon understanding of paleoseismicity within the developing foreland basin recorded as seismites within strata of similar age within Ohio, Kentucky, Virginia (see Pope et al., 1997; Jewell and Ettensohn, 2004; McLaughlin and Brett, 2006). The early work of Martini (1965; 1971) and Friedman et al. (1982) suggesting that ball-and-pillow structures within the Thorold and Grimsby Formations in the Hamilton area may be seismically generated has been confirmed through field studies. When combined with the
U.S. studies within the Michigan and Appalachian basins discussed here, this thesis expands the known extent of Paleozoic seismites both geographically and stratigraphically across both basins that suggest widespread and persistent seismicity during basin development during the Lower Silurian. The broad distribution of seismites supports the model of rapid basin subsidence and compressional tectonics during the Upper Ordovician and Lower to mid-Silurian proposed by Sanford et al. (1985).

5.1.2 Lakefloor sediments – glacial/post-glacial seismicity

High resolution seismic reflection profile data collected from sixteen lakes across Ontario and western Quebec (Gull, Muskoka, Joseph, Rousseau, Ontario, Wanapitei, Fairbanks, Vermilion, Nipissing, Huron, Georgian Bay, Mazinaw, Simcoe, Timiskaming, Kipawa, Parry Sound, Lake of Bays) provides one of the largest such datasets collected to date in eastern North America. This broad regional study, conducted over an area of 100,000 km², confirms that unconsolidated fine-grained sediments deposited in lakes during and after deglaciation about 10,000 ybp are ‘natural seismographs’ displaying a wealth of co-seismic deformation structures. Lakefloor sediments of lakes Nipissing, Muskoka, Joseph, and Parry Sound display lateglacial faulting and slumping likely related to ground shaking during earthquakes triggered by rapid crustal rebound immediately after deglaciation. These lakes lie directly above Precambrian terrane boundaries. Post-glacial deformation in the form of diapirs associated with pits and linear troughs produced by erosion of sediments by escaping fluids or gas (Boyce et al., 2002) is confirmed in Lake Simcoe also above Precambrian terrane boundaries. Lakes Timskaming and Kipawa contain extensive deformation features
associated with seismicity in the Western Quebec Seismic Zone (WQSZ) that can be attributed to modern earthquakes (Timiskaming earthquake of 1935). Lateglacial structures can be readily distinguished from those that affect younger Holocene sediments in lakes Timiskaming and Kipawa along the seismically-active Timiskaming graben. Lake Timiskaming also displays high-angle faults associated with horst and grabens along with open fractures on the lake floor with numerous slumps around the basin margin. Exceptionally thick mass flow successions within Lake Timiskaming suggest a higher frequency of earthquakes and slope failures during glaciation and glacio-isostatic rebound but the faulting and failure of the lake floor sediments confirms that the Timiskaming graben is a weak zone.

The survey of sixteen lake floors confirms the value of sub bottom profiling in interpreting seismically generated deformation structures, expanding upon the initial work of Shilts (1984) and those studies that followed (e.g., Shilts and Clague, 1992; Kelson et al., 1996; Ouellet, 1997; Aylesworth et al., 2000; Talwani and Schaeffer, 2001; Tuttle, 2001; Aylesworth, 2007; Cauchon-Voyer et al., 2008; Doughty et al., 2010a, 2013). This thesis demonstrates the value of these lakefloor sediments for identification of seismogenic structures and the potential for constraining the locations of epicentres of ancient earthquakes. The finding that shield lakes were cleared of any pre-existing sediment by the Laurentide Ice Sheet and only filled during deglaciation is an invaluable one. Deformation structures resulting from glaciotectonic overriding of older sediments, which complicate identification of co-seismic deformations, are absent from these basins unlike those preserved on land (Eyles and Mohajer, 2003; Mohajer et al., 1992). The study furthers understanding of the effects of geologically-recent mid-plate seismicity by specifically identifying the sub
bottom geophysical characteristics of lacustrine deformation structures that are the result of non-seismic processes as well.

5.2 CONCLUSIONS

The compilation of earthquake epicentres in eastern North America presented in Chapter 4 confirms a distinct broad-scale association with major lineaments, suture zones and failed rifts recording the life histories of Rodinia and Pangea. Evidence presented in this thesis, when combined with the current literature, provides a comprehensive database summarizing the geologic record of intraplate seismicity and its relationship to known Precambrian and Paleozoic structures in Southern Ontario (see Tables 5.1 and 5.2; Fig. 5.1). This thesis provides the essential first steps in establishing a relationship between paleoseismicity and reactivation of buried structures within areas of modern intraplate earthquake activity such as the heavily populated western Lake Ontario region and the Ottawa-Timiskaming graben.

Data on paleo-earthquakes presented in this thesis supports the model that ongoing mid-plate earthquake activity in eastern North America is a consequence of brittle deformation of the fractured and faulted upper crust of the North American plate (Dineva et al., 2004; Mazzotti, 2007; Mereu et al., 2013). The precautionary principle suggests that all Precambrian structures in mid-continent North America therefore must be considered potentially seismogenic when assessing seismic risk.
5.3 OPPORTUNITIES FOR FURTHER RESEARCH

This thesis demonstrates that the geologic record of Southern Ontario can fill in the gap left by a limited historical and instrumental earthquake record by identifying potentially seismogenic structures. The enormous potential impact of mid-continent earthquakes on the economy of this heavily populated area (AIR Worldwide, 2013) makes further study a high priority and underscores the need for additional regional-scale study of Phanerozoic seismicity.

Much of the Paleozoic cover strata of Southern Ontario are covered by thick glacial sediments. In areas of exposed strata such as the Niagara Escarpment, outcrops are limited by thick talus debris and often are inaccessible. Work is often limited to quarries where access may be limited and in drill core which is very limited in areas such as the western Lake Ontario region. Laminated sediments of the Eramosa Member of the Guelph Formation have proven to be well suited for the identification of seismites. Similar laminated horizons within the A-1 carbonate unit of the Salina Formation across southwestern Ontario (Coniglio et al., 2004) were deposited during the Upper Silurian at a time that Sanford et al. (1985) suggested was the period of the greatest uplift of the Algonquin Arch and rapid subsidence of the Michigan basin. Our understanding of seismicity of the Michigan basin could be expanded by evaluating these units. Other work in Paleozoic seismicity could be expanded in areas of other “potential” seismites such as the Ottawa Embayment (Bleeker et al., 2010) and the Timiskaming Graben (see Dix et al. 2010).

Lakefloor sediments have proven themselves to be “natural seismographs” documenting post-glacial rebound and the relationship with Precambrian structures and terrane boundaries. The work conducted in this thesis was only a partial survey of the
hundreds of lakes in Ontario and Western Quebec. These studies should be expanded to additional lakes above terrane boundaries and in those lakes that can be considered as ‘controls’. Of particular interest would be expanding the work to lakes in the vicinity of the Central Metasedimentary Belt Boundary Zone to more closely resolve the Holocene history of this complex boundary zone.
Table 5.1: Published evidence of earthquakes in the geologic record of Southern Ontario.

<table>
<thead>
<tr>
<th>Ref. #</th>
<th>Age</th>
<th>Stratigraphic Location/ Unit</th>
<th>Rock/Sediment Type</th>
<th>Structure</th>
<th>Location</th>
<th>Reference</th>
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<td>Homogenized breccias, faulting, fault propagation folds</td>
<td>Wiarton</td>
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<td>Eramosa</td>
<td>Dolostone</td>
<td>Deformed bedding, breccia</td>
<td>Guelph</td>
<td>Brunton, 2009</td>
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<tr>
<td>11</td>
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<td>DeCew</td>
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<td>Ball and pillow</td>
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### Glacial/Lateglacial Record

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Table 5.1 (cont’d): Published evidence of earthquakes in the geologic record of Southern Ontario.

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<td>Lake Timiskaming</td>
<td>Doughty et al., 2013</td>
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<td>Lake Sediments</td>
<td>Slumps, Faulting</td>
<td>Timiskaming</td>
<td>Doughty et al., 2010b</td>
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<td>Thomas et al., 1993</td>
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Table 5.2 - Published evidence of earthquakes within the stratigraphic record of Southern Ontario

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<tr>
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<td>Glacial/Late Glacial</td>
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</tbody>
</table>

**LEGEND (Structures):**
- BP - Ball and Pillow Structures
- BR - Breccia
- D - Deformation (general)
- FF - Folds and/or faults
- LS - Landslide
- PU - Popups
- S - Slumps

**References:**
- Boyce et al., 2002
- Todd and Lewis, 1993
- Jacobi et al., 2007
- Godin et al., 2002; Eyles and Mohajer, 2003; Godin et al., 2003
- Thomas et al., 1993
- McFall and Allum, 1991; Allum, 1993
- McLaughlin and Brett, 2006; this thesis
- McLaughlin and Brett, 2006; this thesis
- Kerr and Eyles, 1991; this thesis
- Dix et al., 2010
- Bleeker et al., 2006
- Bleeker et al., 2006
- Dix and Al Rodhan, 2006
- Adams, 1982
- Aylesworth et al., 2000; Aylesworth, 2007
- Doughty et al., 2010a
- Doughty et al., 2013
- Doughty et al., 2010b
- Godin et al., 2002; Eyles et al., 1993; Godin et al., 2003
- Thomas et al., 1993
- Aylesworth, 2007
- Aylesworth et al., 2000
- McFall and Allum, 1991; Allum, 1993
- McLaughlin and Brett, 2006; this thesis
- Kerr and Eyles, 1991; this thesis
- Dix et al., 2010
- Bleeker et al., 2006
- Bleeker et al., 2006
- Dix and Al Rodhan, 2006
- Adams, 1982
Figure 5.1  Location of seismically related deformation and structures in Southern Ontario. Structural data summarized from Bartholomew and Van Arsdale (2012), Boyce and Morris (2002), Carr et al (2000) and Mazzotti (2007). Earthquake epicentres (Halchuk, 2009; Natural Resources Canada, 2013) along with faults, lineaments and terrane boundaries (Armstrong and Carter, 2010; Atomic Energy Control Board, 2000, Boyce and Morris, 2002; Carr et al., 2000; Daneshfar and Benn, 2002; McFall and Allum, 1989; Ontario Geological Survey, 2011; Sanford, 1993). Refer to Table 5.1 for details. (refer to legend on the following page).
### Figure 5.1 (cont'd) - LEGEND

**Terranes**

| Ah | Ahmic   | Maz | Mazinaw |
|    |         |     |         |
| Alg| Algonquin| Mc  | McCraney |
| All| Alliston| McL | McLintock |
| B  | Britt   | MR  | Moon River |
| BD | Belmont | Mus | Muskoka |
| BT | Bancroft| N   | Novar |
| Be | Beaverstone| NE | Nepewassi |
| C  | Cambridge| O   | Opeongo |
| E  | Elzevier | P   | Powassan |
| F  | Fishog  | PS  | Parry Sound |
| F-A | Frontenac-Adirondack Belt| R | Rosseau |
| G  | Grimsthorp| S  | Seguin |
| GH | Go Home  | SD  | Shawanaga |
| Hun| Huntsville| SL | Sharbot Lake |
| Hur| Huron   | T   | Tomiko |
| HC | Harvey-Cardiff Arch| TL | Tilden Lake |
| Ke | Kent    | W   | Waterloo |
| K  | Kiosk   |     |         |

**Structures**

- Terranes and Boundaries
- Faults
- Major Aeromagnetic Lineament

| CMBBZ | Central Metasedimentary Belt Boundary Zone |
| GFTZ  | Grenville Tectonic Zone |
| GBLZ  | Georgian Bay Linear Zone |
| HLEL  | Hamilton-Lake Erie Lineament |
| HPL   | Hamilton-Presqu'ile Lineament |
| NPLZ  | Niagara-Pickering Linear Zone |

#### Evidence of seismic activity through geologic record

- Paleozoic
- Glacial/Late-glacial
- Post-glacial

#### Faults related to seismicity (Milne, 1992)

1. Central Metasedimentary Belt Boundary Zone Fault
2. Robertson Lake Mylonite Zone
3. Frontenac-Sharbot Lake Terrane boundary aka Napanee-Picton Fault
4. Rideau Fault aka Perth Road mylonite zone
5. St. Lawrence Graben extension
6. Presqu'ile - Hamilton Fault
7. Campbellford-Belleville Fault
8. Clarendon-Linden Fault
9. Picton Fault
10. Salmon Point Fault
11. Salmon River Fault
12. Electric Fault
13. Georgian Bay Linear Zone

**Earthquake Epicentres (magnitudes)**

- <0
- 0…1
- 1…2
- 2…3
- 3…4
- 4…5
- 5…6
- >6
REFERENCES


