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Lake sediments as natural seismographs: Earthquake-related deformations (seismites) in central Canadian lakes

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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. A regional seismic sub-bottom profiling of lakes Gull, Muskoka, Joseph, Rousseau, Ontario, Wanapitei, Fairbanks, Vermilion, Nipissing, 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 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 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 Timiskaming Graben within the seismically-active Western Quebec Seismic Zone (WQSZ), 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. Postglacial neotectonic activity is recorded by co-seismic water-escape structures, faults, slumps and debris flows in Lake Simcoe (above a terrane boundary) and especially within lakes Timiskaming and Kipawa, recording ongoing deformation within the WQSZ. 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.

1. Introduction

Until quite recently, the Canadian Shield and overlying 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. However, as seismic networks have expanded, there is growing recognition of recurring intraplate seismic activity (see Adams and Basham, 1989; Wallach et al., 1998; Tremblay et al., 2003; Dineva et al., 2004; Kim et al., 2006; Dineva et al., 2007; Stein and Mazzotti, 2007; Mereu et al., 2013). New seismic events in unexpected locations reveal 'weak points' in the North American plate and active crustal deformation (Mazzotti, 2007). Recent large earthquakes in eastern Canada include the Timiskaming Earthquake of 1935 (M6.2) which was felt over an area of 2.5 million km^2, and the 1944 (M.5.8) Cornwall Earthquake which to date is Canada's costliest in terms of damage (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 could create $61 billion of damage to infrastructure such as the nuclear generating facilities at Pickering and Darlington near Toronto, Canada's largest city.

Against a backdrop of rapid urban growth and increased awareness of seismic risk in the most heavily populated part of Canada, the origin of mid-plate seismicity is still not well understood but appears to be

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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 is the Western Quebec Seismic Zone (WQSZ; Forsyth, 1981), a belt of enhanced seismic activity that extends from Canada into the coterminous US, that poses a regional risk to mines, critical nuclear facilities and the large urban areas of New York, Montreal and Ottawa (Fig. 1). In the case of Ottawa 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; causal mechanisms are said to be 'elusive' (Bartholomew and Van Arsdale, 2012). 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-known sub-crops of Precambrian structures is not straightforward (Adams, 1992; Wallach et al., 1998; Dineva et al., 2004). Another impediment is that the historic record of earthquake activity only began relatively recently in the early seventeenth century and the instrumental record is also very short (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 glaciated areas 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; Mörner, 2011, 2013). Given the lack of any lengthy historic record in eastern North America, emphasis has been placed on examining the geologic and geomorphic record of seismic activity recorded by the sub-bottom stratigraphy of postglacial lakes and other water bodies (e.g., Shilts, 1984; 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 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). The study area encompasses lake basins across an area of approximately 100,000 km^2 extending from Sudbury in the north, south to Toronto, and from Lake Huron in the west to Timiskaming and Kipawa in western Quebec (Fig. 1, 2, 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 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,

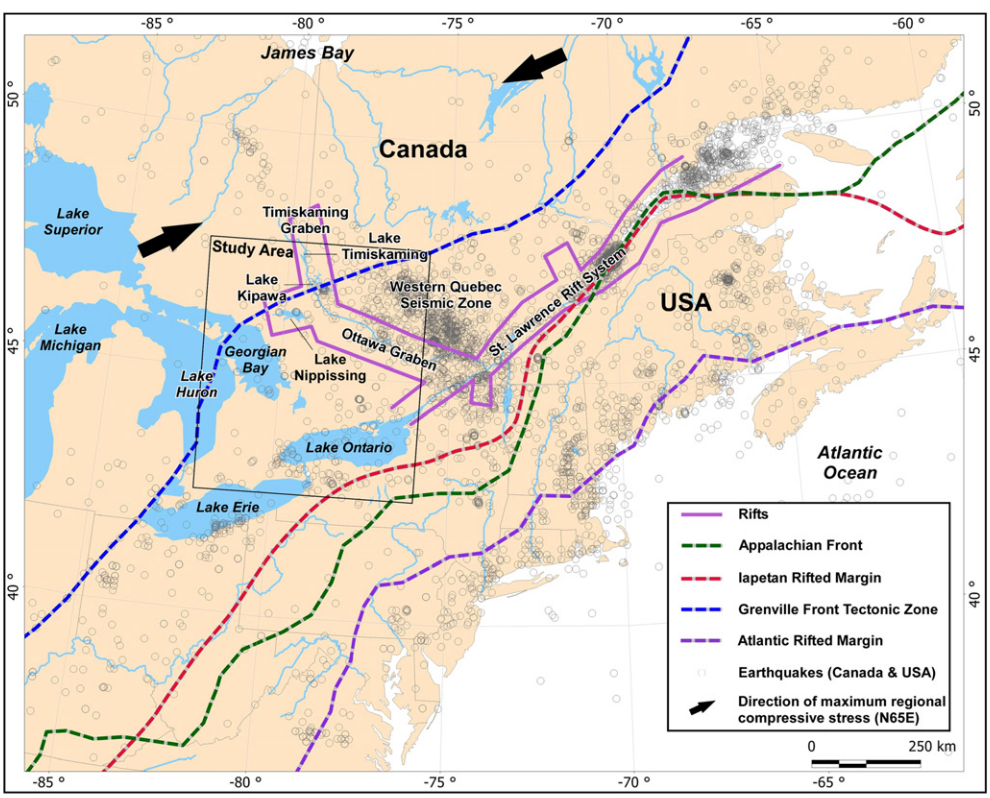

Fig. 1. Broad scale structure of eastern North America resulting from formation and breakup of Rodinia and Pangea with historic earthquake epicentres (1627 to 2013 AD) after Natural Resources Canada (2013), Halchuk (2009) and United States Geological Survey (2010). Major structural boundary locations 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). 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).