

# EARTHQUAKE-INDUCED LANDSLIDING EAST OF OTTAWA; A CONTRIBUTION TO THE OTTAWA VALLEY LANDSLIDE PROJECT

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## ABSTRACT

Evidence based on radiometric age dating and site investigation suggests that the Ottawa region experienced two geologically destructive earthquakes. One, at 4550 yr B.P., caused widespread landsliding in sensitive marine clays. The other, at 7060 yr B.P., caused irregular surface subsidence, lateral spreading, and sediment deformation in thick deposits of marine clay and sand infilling a small deep bedrock basin. Magnitude of these earthquakes probably exceeded 6.5.

## RÉSUMÉ

Des résultats obtenus par datation radiométrique et par investigation in situ suggèrent que la région d'Ottawa a subi deux séismes géologiquement destructeurs. L'un, daté de 4550 a. BP, a provoqué à l'échelle régionale des glissements de terrain dans les dépôts marins d'argile sensible. L'autre, daté de 7060 a. BP, a causé un affaissement irrégulier du sol, des étalement latéraux, et la déformation d'épais dépôts d'argiles marines et de sables remplissent une petite cuvette profonde dans la roche en place. La magnitude de ces séismes a probablement dépassé 6.5.

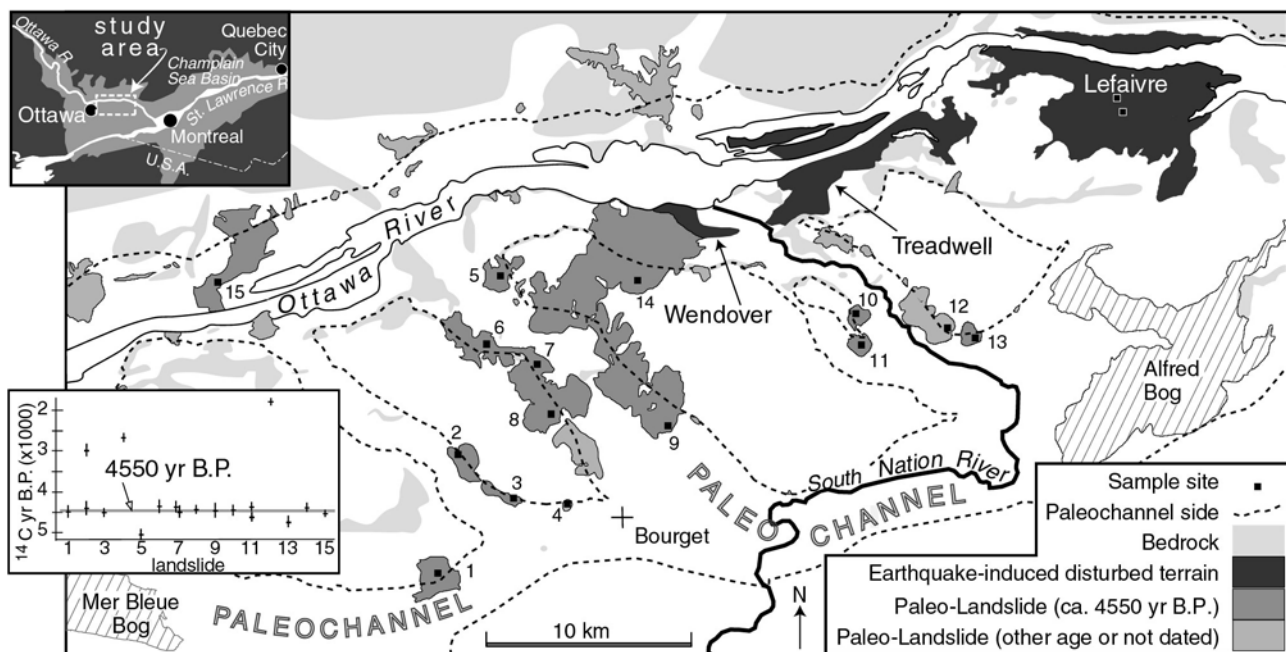


Figure 1. Location of earthquake-induced landslides ca. 4550 yr B.P., and ground disturbance ca. 7060 yr B.P. Ottawa is immediately to the west of the map. Radiometric age (2 $\sigma$  error bars) of landslides in inset.

## 1. INTRODUCTION

The region east of Ottawa was the site of two of the most geologically destructive earthquakes known to have occurred in eastern Canada; one at 4550 yr B.P. and the other at 7060 yr B.P. These events caused widespread landsliding and irregular surface subsidence and sediment deformation. These new discoveries provide evidence that this region, which has experienced only small (magnitude < 4) earthquakes during the historic period, may be subject to occasional high-magnitude earthquakes. This paper will present the geological evidence of these earthquakes, discuss the possible magnitudes and locations

of the epicenters, and summarize the ground motion amplification response to this shaking.

### 1.1 Geological Setting

The study area (Fig.1) lies within the Ottawa Valley, a graben characterized by numerous ancient faults that trend generally east-west parallel to the Ottawa River. The area is mainly underlain by Paleozoic sedimentary rock with Precambrian bedrock forming the northern limit. Earthquakes in the valley are the result of reactivation of normal faults of the Ottawa Graben in a compressional stress regime (Adams and Clague 1993). The West Quebec

Seismic Zone, an area with a high frequency of earthquake occurrences, lies to the north of the study area.

The base of the Late Quaternary sequence filling the Ottawa Valley consists of a generally thin sheet of till and, in places, thin to thick accumulations of glaciofluvial sand, silt and gravel. These sediments are overlain by a thin unit (commonly less than 2 m) of freshwater, rhythmically bedded, fine-grained sediment, which is in turn overlain by a thick marine sequence. The marine sediments average 30 to 50 m thick, but may attain thicknesses of 100 m in a few areas adjacent to the Ottawa River. The marine sequence records an upward change from a deep water, high-salinity, marine environment to estuarine conditions (Gadd 1988). Massive to weakly stratified, gray marine clay at the bottom grades into a coarsening-upward prodelta sequence of rhythmically bedded red and gray clay with thin silt bands and occasional silt or fine sand layers commonly less than 20 cm thick. Commonly known as Leda Clay, the marine sediments are geotechnically sensitive clayey silts and silty clays, mainly composed of non-clay minerals (glacial rock flour). The marine sediments are generally overlain by deltaic sand and silt of the Ottawa delta, which prograded across the area, following the retreating sea (Gadd 1986). Several large paleochannels, now abandoned, of the proto-Ottawa River have been eroded into the deltaic and marine sediments.

A series of four, large, crosscutting, abandoned channels that mark earlier positions of the Ottawa River extend east of Ottawa (Fig. 1). The valleys containing the paleochannels are steep-sided, about 20 to 25 m deep, and 1.5 to 11 km wide, and are underlain by marine clay with a veneer of fluvial sand in places. The interfluvial areas are generally capped by 2 to 10 m of deltaic sand. The channels were abandoned prior to the establishment of extensive, thick peat bogs filling the lowest parts of the valleys. Basal peat from Mer Bleue Bog, in the west, was dated at  $7650 \pm 210$  yr B.P. Basal peat from Alfred Bog, in the east, yielded a date of  $7100 \pm 100$  yr B.P. Most paleochannels were probably abandoned by 8000 yr B.P. when high discharges from glacial lakes to the north and west ceased (Fulton and Richard 1987). With the exception of the South Nation River, only small streams now occupy the other channels. The paleochannel walls are scarred by numerous earthflows (Fig. 1) that are an order of magnitude larger than any historic landslides. These large flows are contained in an area of approximately 50 km by 25 km.

## 2 PALEO-LANDSLIDE AREA

### 2.1 Description of Paleo-landslides

Sizes of individual earthflows range from 1 to 5 km<sup>2</sup> in area (up to about 55 million m<sup>3</sup>). In places, large, overlapping and coalescing slope failures form huge landslide complexes, up to 32 km<sup>2</sup> in area. The earthflows retrogressed up to 1.5 km into the terrace behind and ran out across the floor of the paleochannels up to 2 km. Most of these large landslides show no evidence of post-depositional fluvial erosion.



Figure 2. Typical paleo-landslide (#9, Fig. 1). Dashed line indicates scarp. (N.A.P.L. Airphoto ).

The scale of these earthflows is so large and the relief so subdued that they are almost impossible to distinguish on the ground. On airphotos, however, they are easily recognizable, with bowl-shaped scarps eroded into the valley side and a characteristic 'thumbprint whorl' pattern of low ridges on the surface of the spoil (Figs. 1 and 2). Small ponds may be impounded behind the ridges. The surface is characterized by an irregular pattern of clay and sand areas reflecting the transport of remnants of the sand cap on the underlying liquefied clay.

### 2.2 Age of Paleo-landslides

Organic materials buried in or under the debris were recovered by a variety of methods, including shallow coring into the pond bottoms, deeper drilling into the spoil, and excavations. In one landslide, a buried organic layer with horizontal trees was exposed for more than 300 m in a drainage ditch. The coring/drilling program had about a 40% success rate of encountering organic material. In some samples it was impossible to determine whether or not the wood represented outer tree rings. In total, 17 dates (Fig.1) from 14 landslides located in several different valleys were obtained using conventional and accelerator mass spectrometry radiocarbon dating.

With few exceptions, radiocarbon dates clustered at 4550 yr B.P. (Aylsworth et al. 2000). The narrow range of dates probably indicates a single massive landsliding event. Of the exceptions, one small landslide (#4, Fig.1), is probably a younger event. A record of two separate events was obtained in one core from landslide 2; the younger date

records a reactivation of a portion of the spoil (Aylsworth et al. 1996). The date of  $1870 \pm 80$  yr. B.P. from landslide 12 is from a near-surface sample and may also record a later reactivation of a portion of this large flow. The oldest date ( $5130 \pm 120$  yr. B.P.), from landslide 5, may have come from inner rings of the buried tree.

### 2.3 Discussion of Paleo-landslides

Prior to this investigation, the slope failures were generally attributed to fluvial erosion or drawdown prior to, or immediately after, channel abandonment by the proto-Ottawa River. If this interpretation were correct, the landslide ages would relate to paleochannel development and would likely range from over 8000 to 4600 yr B.P. However, most of the dates lie within a very narrow age range regardless of location and are several thousands of years younger than the time of paleochannel abandonment. The massive discharges that eroded the paleochannels and subsequent drawdown caused by channel abandonment were obviously not factors in triggering the earthflows.

Modern Leda Clay flows often occur during abnormally wet years, in the spring, following snow melt when river levels are changing, ground is saturated and pore pressures are high. It is possible that a significant climate change towards wetter weather ca. 4550 yr B.P. could have induced widespread instability. However, the paleoclimate record suggests that local climate was warmer and dry (Anderson et al. 1989), not optimal conditions for widespread instability.

The most probable single event that could cause trigger widespread massive landsliding is a large earthquake or cluster of closely timed earthquakes. Earthquakes are known to have induced landslides in eastern Canada as in many parts of the world. The Charlevoix earthquake of 1663 caused the greatest ground-shaking episode experienced in Quebec in recorded history and triggered large earthflows in sensitive clay over a wide region of the Saguenay Fjord basin (Desjardins 1980; Filion et al. 1991; Syvitski and Schafer 1996). On the basis of descriptions in the historical record, a magnitude of about 7 has been assigned to this earthquake (J. Adams, pers. comm., 1999). No significant subaerial landslides have occurred during other large, but lesser, magnitude earthquakes in eastern Canada. For example, only small failures happened during the M5.9 Saguenay earthquake of 1988 (Lefebvre et al. 1992). The M6.3 Temiskaming earthquake of 1935 produced local subaqueous slumps that caused turbid conditions in local lakes (Doig 1999). No slope movements were attributed to the M5.8 Cornwall-Massena earthquake of 1944 or the M5.3 Western Quebec earthquake of 1914. The 1914 event, with an epicenter only 41 km away, is the closest large historic earthquake to the study area. The lack of failures generated by historic earthquakes suggests that a strong earthquake is required to create massive, widespread landsliding.

It is also worth noting that the narrow layers of fine sand and silt interbedded with the clay in the upper 20-25 m of the marine sequence may play a role in the initial instability. Initial liquefaction of the sand layers due to earthquake shaking may trigger loss of shear strength and liquefaction

in sensitive clay. In laboratory tests, Konrad and Dubeau (2000) have demonstrated that stratified sand and silt layers induced much lower cyclic resistance than those developed in either of the materials alone. Differential pore pressure generation in each soil unit suggests that water migration can occur from sand layer to silt layer and cause a strength reduction.

## 3 AREAS OF DISTURBED TERRAIN

### 3.1 Description of Disturbed Terrain

To the immediate east of the landslide zone are three areas of disturbed ground within a generally flat plain eroded into Champlain Sea clays by the proto-Ottawa River (Fig. 1). The three areas of disturbed ground are characterized by a very irregular surface and the few exposures in these areas reveal severely deformed bedding (Fig. 3). The ground disturbance occurred after the plain was eroded, because fluvial flutes on the undisturbed erosional surface are truncated at the margins of these disturbed areas. The smallest area, Wendover ( $2.5 \text{ km}^2$ ; Fig. 1), lies at the toe of a large earthflow tongue and may be associated with the landslide. However, the morphology of Wendover's surface is identical to that of the other two areas, Treadwell ( $21 \text{ km}^2$ ) and Lefaivre ( $46 \text{ km}^2$ ; Fig. 1), which are not in contact with earthflows. Two radiocarbon dates (7060 yr B.P. and 7100 yr B.P.) on buried trees establish the date of disturbance within the Lefaivre area.



Figure 3. Deformed sediment in ditch at Wendover. Deformation includes severely contorted, faulted, and upturned beds of clay, silt and fine sand, with ball structures and narrow sand vents from below.

### 3.2 Investigations in the Lefaivre Disturbed Area

In the Lefaivre disturbed area (Fig. 4), the surface morphology gradually changes from gentle undulations and shallow depressions near the margins to rolling and hummocky topography near the centre of the area. Local relief ranges up to 8 metres. Numerous small ponds and wetlands occupy the intervening low areas but no integrated drainage system exists. The elevations of the tops of hummocks are relatively uniform and coincide with the



Figure 4. Lefaiivre area of disturbed terrain. Boreholes 4, 5 and 6 are shown. Sections exposing deformed clay are denoted by x. Sections exposing sand are denoted by s. E denotes shallow exploratory boreholes. Seismic profile of Fig. 8 is indicated by solid line. Location of Fig. 6 indicated by white asterisk. (NAPL airphotos A31010 - #174 and 175).

surrounding level plains. Although the irregular surface somewhat resembles the surface of some massive earthflows, no landslide scarp exists. The margins of the Lefaiivre area merge seamlessly with the surrounding flat clay plain. The surface consists mainly of clay, with random patches of sand. Bedrock is exposed at the surface within a few kilometres of the area in all directions (Figs. 1 and 4).

Severe sediment deformation, ranging from brittle shear to plastic deformation and liquefaction of the Leda Clay, was seen in 3-5 m deep drainage ditches. At three locations, warped, steeply inclined beds of red and gray clay rhythmites are exposed. Small horizontal faults offset some of the inclined clay beds. Occasional sand lenses and a small flame structure have penetrated into the overlying clay, and clusters of minute sand dykes angle across the inclined clay beds. In places, mixing of the red and gray clays has obscured the bedding; in other places, long folded streaks or balls of red clay are incorporated into the gray clay. All these features indicate strong post-depositional disturbance.

Some of the sporadic surface sand patches may be remnants of a fluvial veneer. However, at some locations, small borrow pits expose thicker deposits which seem to form isolated sand bodies within the clay. An investigation

was conducted at one site where sand was found to form the southeastern side of a 100 m wide depression. Probing did not encounter sand elsewhere in the depression. A 40 m long, 1 to 1.5 m deep, trench was excavated from near the centre to the outer upper part of the depression to trace the sand. Several deeper excavations were made along this trench. The sidewall revealed fluvial fine to medium sand overlain at a 45° angle by deformed clay near the edge of the depression (Fig. 5a). At the midpoint of the trench, sand was at least 3 m thick. Sand disappeared under peat near the centre. A deep pit in the centre of the depression exposed 3 m of peat overlying at least 1 m of gray clay. The fluvial structures in the sand (e.g. cut and fill structures, climbing ripples) were more or less intact, although faulted, over much of the length of the trench (Fig. 5b). However, fluidized sand features were common within about 2 m of the contact with the overlying clay (Fig. 5c). This sand deposit occurs as an isolated body within the clay, indicating that it is not in its original depositional location. It is likely that it was part of a larger buried sand deposit and was displaced from below, more or less intact, as a sand dyke during an earthquake. This displacement was probably associated with ground cracking due to minor lateral spreading or *in situ* block rotation. Exploratory drilling nearby penetrated a more extensive, thick sand body 7 m below the surface. This may be the source of the sand dyke.

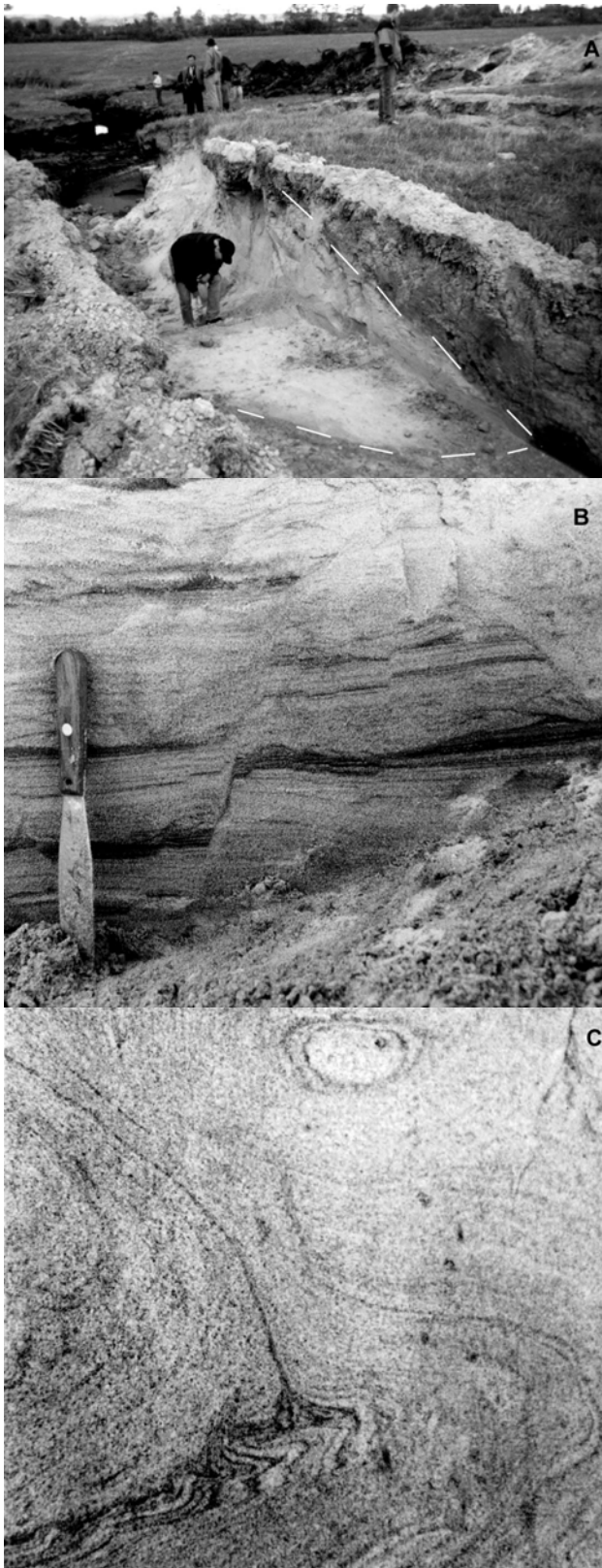


Figure 5. a) Trench across sand dyke. View towards peat-filled centre of depression. Dashed line shows contact with overlying clay. b) Faulted bedding and c) fluidized structures in sand in sidewall.

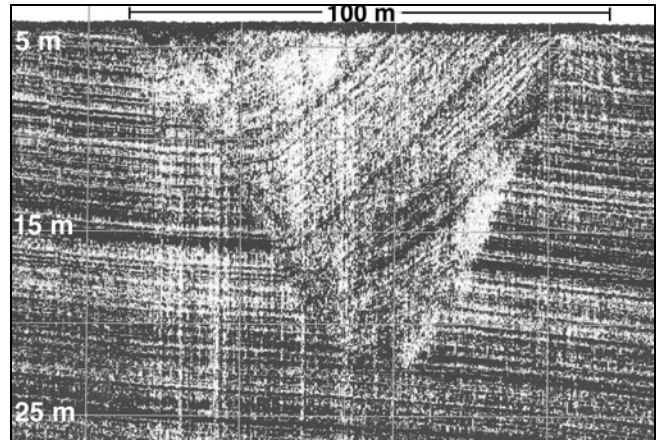


Figure 6. Sub-bottom image of *in situ* rotational block of Champlain Sea sediment. (Douma and Aylsworth 2001).

Evidence of ground deformation extends offshore under the bed of the Ottawa River. Sub-bottom profiling in a regional grid confirmed that deformed sediments were present beneath the river bed and only occur adjacent to the zones of disturbed ground on land (Douma and Aylsworth 2001). Both folding and faulting of Champlain Sea sediments can be observed to at least a depth of 30 m below river bottom. In a few places features interpreted to be sand dykes intrude into the overlying horizontally bedded sediments (M. Douma, pers. comm., 2002). Figure 6 shows an example of a rotational displacement of a layered marine sequence. A 3-dimensional analysis developed from the traverse lines over this feature reveals an *in-situ* rotational displacement of sub-bottom sediments with subsequent truncation by the river. The horizontal size of the feature is comparable to the depressions on shore where inclined bedding and sand dykes have been observed in ditches and excavations.

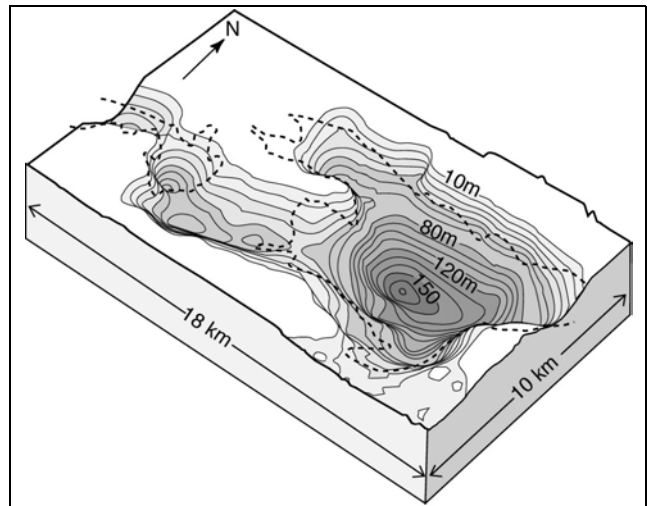


Figure 7. 3-D representation of bedrock surface underlying the Lefaire and eastern Treadwell (on left) disturbed areas, determined by seismic reflection surveys. Dashed overlay represents the disturbed areas, which coincide with deep bedrock basins. (Diagram prepared by B. Benjumea.)



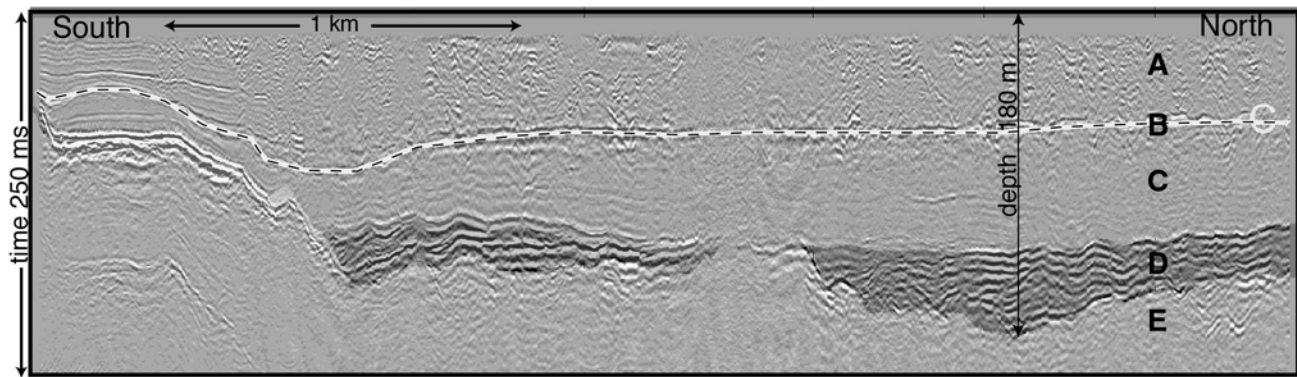


Figure 8. South-to-north compressional wave seismic section across the Lefaivre basin. Unit A is disturbed sediment with poor record. Unit B is a strong reflector that is interpreted to be the base of disturbance over most of the section. Unit C is undisturbed Champlain Sea sediment Unit D is glacial sediment. Unit E is bedrock. (After Benjumea et al. 2003.)

Seismic surveys (Aylsworth and Hunter this volume) have identified a small deep bedrock basin (the Lefaivre basin) underlying the disturbed area and have shown that the confining basin walls of the basin rise sharply (Fig. 7). Deep bedrock basins were also found under Wendover and Treadwell areas. Fifty 1-dimensional seismic reflection soundings revealed that the bedrock surface in the centre of the Lefaivre basin lies about 180 m below the ground surface (150 m below present sea level). Benjumea et al. (2003) have obtained a high-resolution seismic section across the Lefaivre basin, which delineates infra-overburden and bedrock structure (Fig 8). Their section clearly indicates the presence of sediment disruption to a depth of 50 m.

Three deep boreholes were drilled through thick Quaternary sediments and into bedrock and continuous core was collected for logging and testing (Fig.9). One borehole, 150

m in depth, was drilled within the deeper part of the bedrock basin where surface disturbance is greatest. A second borehole is located near the edge of the disturbed area where topographic expression is subdued and the underlying bedrock is closer to the surface (65 m). The third borehole is approximately 1 km south of the disturbed area.

In the deep borehole (Bh4, Fig. 9), geological logging revealed the presence of two thick layers of saturated fine to medium sand at depth within the clay sequence. Deformation in the clay ranges from brittle shear to extreme plastic deformation and liquefaction. In the upper clay unit, at 39 m depth, a 5 cm wide sand dyke extended through a 2.5 m length of core, and the surrounding red and gray clay layers were vertically inclined, convoluted, and folded, — dragged upward with the dyke. Small sand balls were present elsewhere within the core. Liquefaction, intrusion, and other fluidized structures were noted within the two sand layers, although lengths of core with intact fluvial bedding are equally common. Deformation structures are also present, although less common, in the middle clay and lower sand units (Fig. 9). No deformation was detected in the clay beneath the lower sand unit. In the deep borehole, deformation extends to a depth of 50 m (Fig. 9). It is likely that the base of the sediment disruption in the seismic profile coincides with the base of the lower sand unit in this borehole. Deformation is less, both in depth (10 m) and intensity, in the second, shallower borehole, in which the sand layers are less than 0.5 m thick (Fig. 9). Outside the disturbed area, where bedrock is shallower, the sand layers are missing and sediment deformation is absent. Testing revealed that the clay samples, from all three cores, are not geotechnically sensitive, probably because of the high pore water salinity in the samples.

The upper sand layer, which is buried under 7 to 17 m of clay, must be the source of the sand dykes found at surface, such as in the trenched depression. The occurrence of thick buried sand bodies within the Leda Clay is uncommon in the Ottawa Valley and is found only in the Lefaivre and Treadwell disturbed areas (Fig. 1; Gadd 1986). Above the marine limit, extensive glaciofluvial outwash deposits fill the valley of the Rivière Blanche to the north. We postulate that

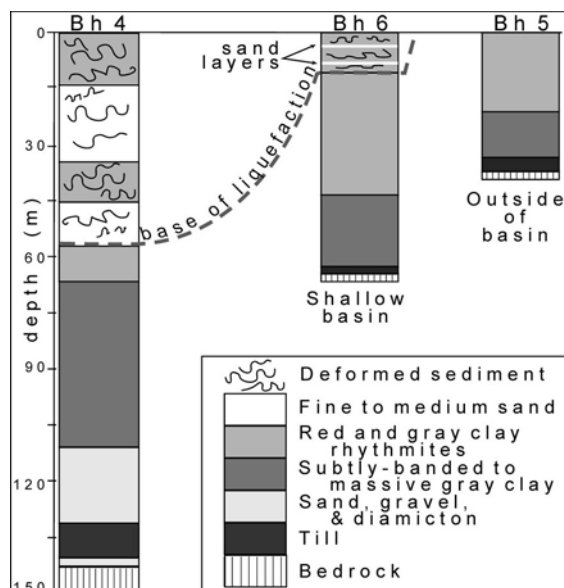


Figure 9. Geological logs of cores from within and adjacent to the Lefaivre disturbed area.

the buried sands at Lefaire and Treadwell are deltaic deposits of two large, rapid, fluvial or glaciofluvial drainage events down the Rivière Blanche. The deep basins were sediment traps, preventing the deltaic sediments from spreading across a larger area.

### 3.3 Discussion of Disturbed Terrain

A strong case can be made that the Lefaire area and probably also the Treadwell and Wendover disturbed areas are the result of a large earthquake. The event at Lefaire occurred ca. 7060 yr B.P. Because of close proximity and similar geological conditions, we infer that the other two areas were created by the same earthquake. A thick deposit of unconsolidated sediments filling a deep, steep-sided, bedrock basin, which is crossed by several faults in a known seismic zone, would be susceptible to deformation due to ground shaking. Ground motion, probably amplified by the bedrock basin, would cause liquefaction of the underlying saturated sands and loss of shear strength, deformation, and possible liquefaction of the clays, resulting in the observed deformed bedding and irregular ground subsidence. Lateral spreading, *in situ* rotation of blocks of sediment, and differential settlement resulting from this liquefaction produced the hummocky topography. The thickness of the clay cap (up to 17 m) probably explains the paucity of sand boils and dykes over much of the area.

Compressional and shear wave reflection and refraction methods were used to establish both the average shear wave velocities for the total thickness of unconsolidated overburden and the near-surface shear wave velocity distribution with depth. These methods were also used to determine the fundamental site period for resonance amplification studies.

Leda Clay is characterized by low shear wave velocities. During an earthquake, thick sequences of these low velocity sediments may experience broad-band amplification of ground motion due to shear wave velocity gradients within the soil column (Aylsworth and Hunter this volume). Significant low frequency amplification may result. In a comparison of seismograph records for a thick sediment site near borehole 4 and another on a nearby bedrock outcrop, M. Lamontagne (pers. comm., 2002) reported a six times amplification for small quakes over a four month monitoring program. Thick sequences of low shear wave velocity sediments may also experience resonance amplification of earthquake ground motion at specific earthquake frequencies (0.3 to 1 Hz range). This resonance amplification (> eight times at the fundamental site period) is due to significant seismic impedance contrasts within the soil or at the soil-bedrock contact (Aylsworth and Hunter this volume). Large fundamental site periods correlate directly with thick overburden, and both coincide with areas of known surface disturbance (Aylsworth and Hunter this volume; Benjumea et al. 2003). B. Benjumea (pers. comm., 2003) reported a close correlation between the fundamental site periods predicted from shear wave reflection soundings and spectral peaks determined using the so-called "Nakamura" method of teleseismic noise measurement.

## 4. MAGNITUDE OF THE EARTHQUAKES

The geological site conditions in the study area were sufficiently responsive to ground motion amplification effects to induce rapid earthflows in the case of the paleo-landslides and sediment deformation and liquefaction, *in-situ* block rotations, lateral spreading and irregular ground subsidence in the areas of disturbed terrain. The magnitude of these earthquakes can be estimated by comparison with other earthquakes known to have produced widespread landsliding and terrain disruption.

Obermeier (1996) suggested that a magnitude exceeding 6 is necessary to cause massive liquefaction. Tuttle and Schweig (1995) estimated that magnitude 6.4 was the minimum magnitude required to induce liquefaction in the New Madrid seismic zone, and that many of the prehistoric earthquakes, identified by liquefaction features in this zone, are estimated to be magnitude 7 or 8.

In a study of earthquake-induced landslides worldwide, Keefer (1984) showed that there are threshold magnitudes below which seismic events rarely cause specific types of landslides. Also, above these thresholds, there are bounds on the distance from the epicenter or fault rupture at which an earthquake of given magnitude is likely to cause landslides. He concluded that a minimum magnitude of 5.0 is necessary to induce soil lateral spreading and rapid earthflow. However, in his survey, few events, with relatively few lateral spreads or flows per event, occurred below magnitude 6.8. It should be noted that Keefer's relationships were derived from a range of geological conditions worldwide, and few of the examples involved sensitive clay.

If the size (~1250 km<sup>2</sup>) of the area affected by landsliding at 4550 yr B.P. in the Ottawa Valley is applied to Keefer's magnitude-area curve, the minimum possible magnitude is 6.2. The estimated area is based on the extent of the sampling program; the area impacted may actually have been larger, thereby implying a greater magnitude earthquake. Worldwide averages for lateral spreads and flows also suggest that the actual magnitude may be greater (Keefer 1984). On this basis, it is estimated that the earthquake that triggered the earthflows ca. 4550 yr B.P. was at least M6.2 and likely at least M6.5.

Keefer (1984) also concluded that, for soil lateral spreads and flows, the epicenter or fault rupture is likely to be close. For a magnitude 6.5 earthquake, landsliding could occur within a maximum distance of 50 km and a probable distance of 20 km. Maximum distance would increase to 100 km and probable distance to 45 km for a M6.8 event.

Based on the scale of the surface disturbance and the depth of sediment deformation at Lefaire, and on comparison with earthquake-induced liquefaction elsewhere (Tuttle and Schweig 1995; Obermeier, 1996), the earthquake at 7060 yr B.P. is also estimated to be at least M6.5.

Using the present seismicity of eastern Canada, the established attenuation limitations, and accepted NEHRP liquefaction boundaries and measured geophysical and

geotechnical site parameters, Benjumea et al. (2003) calculated that a M6.5 earthquake located within 20 km would cause liquefaction to a depth of 30 m at Lefavre.

## 5. CONCLUSIONS

Widespread, large earthflows in the paleochannels east of Ottawa were probably triggered by a large earthquake about 4450 yr B.P. Seismic shaking disturbed sensitive clay slopes, causing the clay to liquefy. Initial liquefaction of narrow, fine sand layers in the upper portion of the marine sequence may have initiated this process. From estimates of the magnitude necessary to induce liquefaction and earthflow (Keefer 1984; Tuttle and Schweig 1995; Obermeier 1996), we infer that the earthquake probably exceeded magnitude 6.2, and may have exceeded magnitude 6.5. A conservative estimate of the distance to the epicenter/rupture centre places it within a radius of 50 km (after Keefer 1984).

The areas of disturbed terrain and deformed sediment at Lefavre, Treadwell and Wendover are also interpreted to be the result of seismic shaking, at about 7060 yr B.P. (at least for the Lefavre area). Ground motion, probably amplified in the thick deposits infilling deep bedrock basins, caused liquefaction of the buried saturated sand bodies, leading to loss of shear strength, deformation, and possible liquefaction of the clay. Lateral spreading, *in situ* rotation of blocks of sediment, and differential settlement resulting from the liquefaction produced the hummocky topography. The earthquake probably was magnitude 6.5+ and occurred within 20 km of the site.

## ACKNOWLEDGMENTS

The authors thank J. A. Hunter and B. Benjumea for their geophysical contributions to this project and G.R. Brooks and J.J. Clague for insightful comments on this manuscript.

## REFERENCES

- Adams, J., and Clague, J.J. 1993. Neotectonics and large-scale geomorphology of Canada. *Progress in Physical Geography*, **17**: 248-264.
- Anderson, T.W., Mathewes, R.W., and Schweger, C.E. 1989. Holocene climatic trends in Canada with special reference to the Hypsithermal interval. *In* Quaternary geology of Canada and Greenland. *Edited by* R.J. Fulton. Geological Society of America, v. K-1, pp. 522-528.
- Aylsworth, J.M., and Hunter, J.A.. 2003. The Ottawa Valley Landslide Project: a geophysical and geotechnical investigation of geological controls on landsliding and deformation in Leda Clay. this volume.
- Aylsworth, J.M., Lawrence, D.E., and Evans, S.G. 1997. Landslide and settlement problems in sensitive marine clay, Ottawa Valley. Geological Association of Canada, Mineralogical Association of Canada, Joint Annual Meeting, 1997, Ottawa, Field Trip B1, 63 p. (fieldguide).
- Aylsworth, J.M., Lawrence, D.E., and Guertin J. 2000. Did two massive earthquakes in the Holocene induce widespread landsliding and near-surface deformation in part of the Ottawa Valley, Canada. *Geology*, **28**: 903-906.
- Benjumea, B., Hunter, J.A., Aylsworth, J.M., and Pullan, S.E. in press. Application of high-resolution seismic techniques in the evaluation of earthquake site response. *In* Contributions to neotectonics and seismic hazard from shallow geophysical imaging. *Techonophysics, Special Volume*.
- Desjardins, R. 1980. Tremblements de terre et glissements de terrain: Corrélation entre des datations au  $^{14}\text{C}$  et des données historiques à Shawinigan, Québec. *Géographie physique et Quaternaire*, **34**: 359-362.
- Doig, R. 1999. Effects of strong seismic shaking in lake sediments, and earthquake recurrence interval, Temiscaming, Quebec. *Canadian Journal of Earth Sciences*, **28**: 1349-1352.
- Douma, M., and Aylsworth, J.M. 2001. High resolution sonar profiling of glacial and post-glacial sediments in the Ottawa River near L'Orignal, Ontario. *In* Current research. Geological Survey of Canada Paper 2001-D4.
- Fillion, L., Quinty, F., and Begin, C. 1991. A chronology of landslide activity in the valley of Rivière du Gouffre, Charlevoix, Québec. *Canadian Journal of Earth Sciences*, **28**: 250-256.
- Fulton, R.J., and Richard, S.H. 1987. Chronology of late Quaternary events in the Ottawa region. *In* Quaternary geology of the Ottawa region, Ontario and Québec. *Edited by* R.J. Fulton. Geological Survey of Canada Paper 86-23, pp. 24-30.
- Gadd, N.R. 1986. Lithofacies of Leda Clay in the Ottawa Basin of Champlain Sea. Geological Survey of Canada, Paper 85-21.
- Gadd, N.R. (editor). 1988. The late Quaternary development of the Champlain Sea basin. Geological Association of Canada, Special Paper 35.
- Keefer, D.K. 1984. Landslides caused by earthquakes. *Geological Society of America Bulletin*, **95**: 406-421.
- Konrad J.-M., and Dubeau, S. 2000. Cyclic strength of stratified soil samples. *In* Proceedings of the 55<sup>th</sup> Canadian Geotechnical and 3<sup>rd</sup> Joint IAH-CNC and CGS Groundwater Specialty Conferences, Niagara Falls, pp. 89-94.
- Lefebvre, G., Leboeuf, D., Hornych, P., and Tanguay, L. 1992. Slope failures associated with the 1988 Saguenay earthquake, Québec, Canada. *Canadian Geotechnical Journal*, **29**: 117-130.
- Obermeier, S.F. 1996. Use of liquefaction-induced features for paleoseismic analysis – An overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleo-earthquakes. *Engineering Geology*, **44**: 1-76.
- Syvitski, J.P.M., and Schafer, C.T. 1996 Evidence for an earthquake-triggered basin collapse in Saguenay Fjord, Canada. *Sedimentary Geology*, **104**: 127-153.
- Tuttle, M.P., and Schweig, E.S. 1995. Archeological and pedological evidence for large earthquakes in the New Madrid seismic zone, central United States. *Geology*, **23**: 253-256.