76. SONAR EVIDENCE FOR POSTGLACIAL TECTONIC INSTABILITY OF THE CANADIAN SHIELD AND APPALACHIANS

Project 690095

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Abstract

Establishing the timing and location of prehistorical seismic or neotectonic events is important for assessing seismic risk, particularly in the design or location of radioactive waste disposal sites or nuclear power plants. Sonar surveys of lakes of the Canadian Shield and Appalachians have revealed two types of evidence of postglacial (neotectonic) instability: 1) slumping of bottom sediments to form mudflows in response to shaking of the lake basin during a seismic event and 2) fracturing or tilting of glacial and modern sediments by differential movement of underlying bedrock. Large-scale tilting appears to have played a role in the formation of the Lac Deschenes segment of Ottawa River. Fluvial erosional forms appear to be drowned beneath Lac Deschenes by uplift of a bedrock dam at the east end of the lake at some time in the last 10,000 years. Care must be exercised in differentiating paleoseismic or neotectonic features from similar-appearing structures or forms produced by glacio-tectonic processes or by nonseismic slope failures.

Résumé

Il est important de situer de façon géographique et temporelle les événements sismiques ou néotectoniques qui ont eu lieu avant l'époque historique, pour évaluer la stabilité à long terme de structures sensibles aux séismes, comme les centrales nucléaires. En effectuant par sonar le levé des lacs du Bouclier canadien et des Appalaches, on a découvert deux types d'indices d'une instabilité postglaciaire (néotectonique) du terrain: 1) le glissement et décollement des sédiments du fond de ces lacs, qui donnent lieu à des coulées boueuses, lorsqu'un séisme secoue le bassin lacustre et 2) la fracturation ou le basculement des sédiments glaciers et des sédiments récents, par mouvement différentiel du soubassement. Il semble qu'un important basculement ait contribué à former le segment du lac Deschenes, dans la rivière des Outaouais. Il semble que des formes d'érosion fluviatile aient disparu au-dessous du lac Deschenes, le soubassement ayant été soulevé et ayant formé un barrage à l'extrémité de ce lac à un moment donné au cours des 10 000 dernières années. Il faut user de prudence lorsqu'on cherche à différencier des phénomènes paléoseismiques ou néotectoniques de structure ou forme similaires produits par des événements glacio-tectoniques, ou des ruptures de pente d'origine autre que sismique.

INTRODUCTION

The numerous small lakes of the glaciated terrain of Canada offer a unique opportunity to study the incidence of late glacial and postglacial tectonic disturbances. The frequency and intensity of seismic activity that accompanies tectonic (or glacioisostatic) adjustments may have an important bearing on the suitability of sites or regions for the construction of structures such as radioactive waste disposal facilities or nuclear power plants. This paper presents selected examples of lake sediment disturbance thought to be related to seismic or neotectonic activity.

Lakes are generally quiet-water settling basins, and they received large amounts of fine grained mineral sediment during the latter stages of deglaciation. They have continued to accumulate fine grained minerogenic and organic sediment at a much slower rate throughout the Holocene. Because of their texture and water saturation, these sediments are particularly prone to disturbance by seismic events, especially where they lie on submerged slopes. The organic nature of the postglacial sediment can allow dating (¹⁴C) of disturbed sediment, and the laminated nature of the clastic lacustrine sediment can provide clear visual evidence of offsets, slumping, or channel cutting related to seismic shock or to differential movements of the underlying bedrock floor. In addition, distinctive patterns of acoustical reflections (caused by sediment lamination), where disrupted, can allow age relationships of erosional or slump features to be estimated.

Several seismic studies of lakes and marine environments have been carried out over the past decade in the North American west (e.g., Sims, 1975; Otis et al., 1977; Qamar et al., 1982; Field et al., 1982; Prior et al., 1982) and in New York (Wold et al., 1977) in an attempt to estimate paleoseismic conditions and the effect of modern earthquakes. Shilts et al. (1976), Klassen and Shilts (1982), and Shilts and Parkh (1982) have studied glaciolacustrine faulting and deformation of glaciaulacustrine and late glacial marine beds under modern lakes. Kenny and Balins (1973) have discussed the bathymetry and probable geotechnical properties of unconsolidated sediments of the Lake Timiskaming basin.

Sedimentation and Disturbance of Lake Sediments

Lakes of the Canadian Shield and Appalachians are generally floored by 1 to 5 m of gyttja, a water-saturated organic sediment composed of autochthonous and allochthonous algal, plant, and animal remains with minor clastic components. Modern sediment in nearshore areas or in areas adjacent to major inflow streams is generally sandy or bouldery. In many lakes, these distinctive modern sediments are underlain by substantial thicknesses of proglacial clastic, laminated, fine grained sediments that rest directly on bedrock or on till.

¹ The physical properties and genesis of lake sediments described in this paper are generally inferred from their acoustic properties as recorded on sonar records. Klassen and Shilts (1982) described the type of coring and comparative studies on which these inferences are based.
Many glacial and nonglacial processes can trigger or cause slumping or deformation of the various types of unconsolidated sediments that occupy lake basins. Where proglacial lacustrine sediments are thick, they are commonly deformed by diapirism, folding, and faulting (Shilts et al., 1976; Klassen and Shilts, 1982; Shilts and Farrell, 1982) which mark collapse over buried glacial ice. In many places detached remnants of glacier ice were preserved in the hollows now occupied by lakes as the glacier backwasted under conditions that must have caused progressive stagnation of its retreating terminus. The occurrence around many lakes of glaciofluvial sediments, which require a temporary ice floor to allow unrestricted drainage, supports the inference that ice blocks were commonly left in lake basins while active sedimentation was taking place. In some cases the laminated sediments were deposited around more slowly melting ice blocks which persisted until after glaciolacustrine sedimentation ceased, leaving sediment-free holes or "ice-block casts" in the lake bottom, flanked by steep ice-contact faces of thick, laminated sediment. A rotational slump block, probably unrelated to seismic activity, was noted on one of these oversteepened faces (Fig. 76.1).

Slumps and disruption of fine grained sediments also may occur during the late glacial sedimentation phase as a result of various processes associated with rapid deposition of sediment from an ice front within the drainage basin. In postglacial time, sedimentation rates are usually relatively slow, the sediment is generally organic, and chances for slumping are low. Nevertheless, groundwater inflow, floods producing abnormally high sedimentation rates, man's interference with the shoreline or bottom, and other nonglacial processes may account for sediment slumping or deformation.

Although soft-sediment slumping or deformation may be caused by any of the processes mentioned above, certain bottom and subbottom features are best explained as response to postdepositional seismic or tectonic events. The deformed sediments in the Canadian Shield and Appalachian lakes described in this report were probably disturbed by

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**Figure 76.1.** Profile of Maple Lake near Haliburton, Ontario; length of profile is approximately 1750 m. Trenches are "ice-block casts"; slopes cutting the laminae are ice contact in origin. Note the rotational slump block on left-hand slope and the covering of acoustically clear gyttja over proglacial laminated sediment.

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**Figure 76.2.** Location map of Lac Tee – Lake Timiskaming region. Mudflow trench is the site of profiles in Figure 76.9. Dashed lines are traces of some of the sonar profiles.
Figure 76.3. Profile of Lac Tee showing hummocky nature of mudflows composed of gyttja thrown from west-facing (right-hand) side of lake (1200 m long). Arrows indicate slumped sediment.
Areas of accumulation of sediment displaced from slopes by 1935 earthquake

Figure 76.4. Bathymetric map of Lac Tee showing areas of accumulation of hummocky sediment dislodged and redeposited during the earthquake of November 3, 1935.
neotectonic processes. It should be borne in mind that they represent only a small proportion of the deformed sediments noted in these and other lakes and that all the rest are more reasonably attributed to neotectonic processes.

Several sediment structures, when interpreted in combination with bathymetric and stratigraphic data, are indicative of seismic or neotectonic disruption:

1. Mudflows, which form distinctive hummocky (or ridged) masses on the normally smooth depositional surface of the lake bottom, are commonly triggered by seismic activity (see also Field et al., 1982). The hummocky surfaces may be associated with trenches eroded by the flow debris into soft sediments upslope from the deposit. Seismically induced slumps are generally unidirectional, that is, they occur only on slopes with similar orientations. They often originate simultaneously from several places or slopes at the same time. Widespread occurrence of contemporaneous multiple slump features in a single basin would be unlikely to be caused by any process other than seismic shock. Where slump deposits are buried by any later sedimentation, sonar profiles can help to establish their contemporaneity.

2. Faulting that penetrates both proglacial and modern sediments, and cannot be related to gravity slumping of a free face, is most likely caused by neotectonic displacements in the underlying bedrock surface. If the faulting can be traced down to bedrock, this is almost certain evidence of neotectonic movement.

3. Subaqueous slump features in lakes known to be in areas of strong, historically documented earthquakes are, of course, easily related to seismic shock.

4. Channels and other features clearly cut into postglacial sediments by fluvial action and now submerged in natural lakes were probably drowned as a result of neotectonic tilting or faulting of the underlying bedrock. Where such topography has been observed, it has the appearance of the bottom of a man-made reservoir.

TECTONIC AND SEISMIC DEFORMATION

Tee Lake
In 1935, a severe (6.2 on Richter Scale) earthquake occurred near the town of Témiscaming, Québec, just east of the south end of Lake Timiskaming (Fig. 76.2). Hodgson (1936) reported that Lac Tee, a small, deep lake located midway between lakes Timiskaming and Kipawa, appeared milky, presumably from soft-sediment disturbance, for several weeks after the earthquake. Sonar profiles of Lac Tee, carried out in 1982, revealed the probable reason for the milky appearance of the water after the earthquake: gyttja on many of the west-facing subaqueous slopes of the lake had slumped from the steeper slopes (>20°) and moved, probably as coalescing mudflows, onto the lake's bottom, forming hummocky deposits (Fig. 76.3). The areas where disturbed sediment was deposited have been mapped and superposed on a preliminary bathymetric map compiled from 35 sonar profiles (Fig. 76.4). The unidirectional displacement agrees well with Hodgson's (1936) deductions that the earthquake's strongest lateral component of movement was eastward. Similar disturbed sediments were found in Lac Kipawa, a few kilometres to the east, particularly in those parts closest to Lac Tee.

Lac Mégantic
A similar hummocky slump deposit was subsequently noted in Lac Mégantic, in the southern Québec Appalachians (Fig. 76.5). Sediment near the top of a steep subaqueous slope flowed down the slope, cutting a trench from which it debouched as a mudflow well out onto the flat, gyttja-covered floor of the lake. Although several other processes could trigger such slumping (rapid sedimentation from inflow streams, groundwater flow, etc.), seismic activity should certainly be considered as a triggering mechanism as none of the neotectonic processes are likely to be important in the vicinity of the slump. Lac Mégantic lies in an area where considerable neotectonic movement has been proposed by Oliver et al. (1970), but little historical seismic activity has been reported in the region.

Lake Dore
Lake Dore, near Eganville, Ontario, occupies a depression in a graben floored by Paleozoic sediments and surrounded by Grenville-age crystalline and metasedimentary rocks. It lies below postglacial marine limit but may have been blocked from the sea because of the configuration of the retreating ice. In any case, it can be seen to be underlain by a thick sequence of fine-grained laminated sediments (Fig. 76.6). Much of the late glacial sedimentary record along the southeast side of Lake Dore is disrupted by a mass (or several masses) of sediment that apparently slumped westward into the basin, disrupting a significant part of the lake bottom (Fig. 76.6). This event(s) occurred before the termination of deposition of laminated sediment, because the slumped mass is overlain by undisturbed laminated sediment which is in turn mantled by postglacial gyttja. The unidirectional slumping is reminiscent of that caused by the Timiskaming earthquake in Lac Tee and may represent a significant late glacial seismic event.

In the profile reproduced here, a series of faults have disrupted almost the entire laminated sediment pile in the central part of the lake, but they clearly postdate the slumping event, the distinctive sequence of beds that overlies the slump deposit being cut by the faults. The faulting is similar to that reported by Qamar et al. (1982) from Flathead Lake, Montana, and appears to extend to bedrock, suggesting that the bedrock surface has risen as much as 5 m under the central part of the lake as a result of some form of postglacial stress. This feature is possibly a "pop-up" structure similar to those documented from quarries in Paleozoic limestones elsewhere in southern Ontario (Adams, 1981).

Lac Deschênes
Lac Deschênes is a ponded section of Ottawa River, lying between Ottawa and Arnprior, Ontario (Fig. 76.7). It is dammed by a low ridge of Paleozoic sedimentary rock at Deschênes Rapids in Ottawa. The profiles that illustrate the subbottom of Lac Deschênes show that the thick fill of fine-grained laminated sediment that underlies the north side of the lake is cut on the south side by a channel formed since its deposition (Fig. 76.8). The laminated sediments are interpreted to be of marine origin, deposited between about 12 000 and 10 000 years ago (Richard, 1975), because thick, fine-grained sediments exposed on land on either side of Lac Deschênes were deposited in the Champlain Sea. The flat surface of the laminated sediment under the north side of the river is cut by numerous small channels, many of which have an acoustically opaque fill which is interpreted to be sand. East of Alymer Island, in the broad eastern bay of Lac Deschênes, sediment interpreted to be gyttja directly overlies bedrock and forms a cover 1 to 3 m thick. No trace of the small channels or of the large channel can be found in this part of the lake. The channel can be traced westward to Constance Bay (Canadian Hydrographic Service, 1982); west of Constance Bay, Ottawa River is underlain by laminated sediment that shows only minor evidence of fluvial erosion.
Figure 76.5. Profiles across Sandy Bay of Lac Mégantic, Québec (A, 2000 m long) and across a mudflow trench parallel to northeast-facing slope of Sandy Bay (B approximately 100 m long). Mounds up to 5 m high on the bottom are flow ridges.
Figure 76.6. Profile of Lake Doré, near Eganville, Ontario, showing massive slump that occurred early in postglacial time (arrow). Faulting in the centre of profile seems to have occurred shortly thereafter and to be caused by fracturing or uplifting of bedrock. Length of profile is approximately 3000 m.

Figure 76.7
Location map of Lac Deschénes area showing the location of the profiles given in Figure 76.8 and the approximate position of submerged channel. Constance Bay is about 8 km west of Dunrobin Shore.
Figure 76.8. Sonar profiles of Lac Deschênes west of Aylmer Island. Profiles are arranged from southeast (top) to northwest (bottom). (See Fig. 76.7 for locations.)
Figure 76.9. Profiles across a trench created by subaqueous mudflow in the north part of Lake Timiskaming. A. Location of the trench on the profile extending to Mann Island; note surface sediments draped over "pillars" of laminated sediment thought to have been deposited in crevasses in stagnant ice. B. Profiles of the mudflow trench from the east end (top) to the west end (bottom). Note diapirism and general disturbance of older proglacial sediment beneath the trench.
Figure 76.10. Faulting of modern sediment in Lake Timiskaming. A. Faulting (arrows) in thick, modern sediment just south of the mudflow trench north of Mann Island. B. Faulting (arrows) and possible diapirism (*) in a deep trench near the narrows.
The large channel is about 13 m deep at its eastern end and deepens westward to more than 40 m west of Dunrobin. It is floored by more than 2 m of sediment that is generally acoustically transparent (fine grained). It is presently a site of deposition rather than erosion. Its southern side is underlain by a bedrock wall which extends as low cliffs exposing Precambrian rocks for 5 m or more above water level.

The general aspect of the sonar profiles of Lac Deschênes suggests those that would be expected in a lake created by damming a river. The channels may have formed during a period of subaerial exposure before flooding of this part of the valley to form Lac Deschênes. If so, this segment of Ottawa valley has been tilted down to the west, at right angles to the regional pattern of glacioisostatic uplift, since cessation of marine deposition above 10 000 years ago (Richard, 1975). If this conclusion is correct, Ottawa valley has been subjected to major neotectonic movement, but it is impossible to deduce from the information presently available whether such movement occurred during a short period or has been ongoing. The following inferences from the sonar records support the conclusion that this area has been tilted in postglacial time:

1. The major channel is cut into postglacial marine sediments which have bedding that intersects its sides in a horizontal attitude. Marine deposition ceased in this part of the valley about 10 000 years ago.

2. The major channel is cut over 45 m below the present bedrock barrier which ponds Lac Deschênes.

3. The major channel is presently a site of sediment deposition, suggesting that the current that cut it is not presently active.

4. The channel deepens to the west, at a gradient opposite to the flow of the river.

5. The small channels cut into the flat surface of the laminated sediments are of a size and spacing reminiscent of gullies presently being cut into similar sediment onshore.

6. The small channels are draped by a sediment layer similar to that occurring in the large channel, suggesting that the forces that cut them are not presently active.

7. Bedrock in the shallow eastern bay of the lake is covered by a sediment with the acoustical properties of gyttja, a sediment not likely to have been deposited if any strong current existed now or in the past.

Lake Timiskaming

The northern and central parts of Lake Timiskaming were studied in 1983 to determine if a seismic event(s), similar to those that affected Lac Tee and Lac Kipawa near its southern end, had affected Timiskaming. Interpretation of more than 200 km of profiles obtained is incomplete at this time, but some intriguing features were noted and are discussed briefly here.

Lake Timiskaming lies in a graben. The northern part of the lake is underlain by flat-lying Paleozoic limestone, but except adjacent to its northern bays, Precambrian rocks outcrop on shore. Two acoustically distinct sediment facies underlie the lake. The older has strong, generally horizontal internal reflections and is thought to comprise varved sediments of glacial Lake Barlow (Vignaud and Hardy, 1979) which cover the lowlands north and east of the lake and which are being actively eroded by Blanche River, Ottawa River, and Wabi Creek. Overlying the glacial sediments with marked angular unconformity is a thick (10 to >30 m) sequence of clayey, largely elastic sediments with weak internal reflections. This sequence is thought to represent Holocene deposition of sediments derived from erosion of the proglacial sediments exposed around the lake, particularly in the north. The great thickness and elastic character of these sediments is unique to Lake Timiskaming and contrasts sharply with the 3 to 4 m thickness of organic gyttja that comprises the Holocene sediment of most southern Canadian Shield lakes.

In the north-central part of the lake, between Mann Island and Dawson Point, a 10 to 15 m-deep trench has been cut through the upper sediment down to its contact with the underlying proglacial sediment (Fig. 76.9). Beneath this trench the proglacial sediments in places are highly disturbed, being deformed by what appear to be diapiric structures formed in laminated sediment and rising from some depth (Fig. 76.9). Presently the trench is interpreted as the result of a major, east-trending depression of proglacial sediments which has left a depression which is in places covered by disturbed debris from the head of the flow. The diapiric structures may have been formed in response to sudden unloading of the area of the trench with accompanying differential loading by the thick sediments that flank it. Alternatively, but less likely, the disturbed structures may be related to movements in bedrock below the trench. As there is no detectable sediment age above the trench, it is likely that the mudflow and its triggering mechanism were active quite recently, possibly within the last thousand years, judging from the high sedimentation rates (estimated to range between 0.1 and 0.5 cm/year) elsewhere in the lake. Because of its location in the middle of the lake and the relatively gentle slopes surrounding the trench, it is thought that the triggering mechanism was probably seismic shock or movement on a fault in the underlying bedrock, rather than a nonseismic slope failure.

Faulting and slumping of modern sediments were also noted north of Mann Island and in the steep-walled portions of the Lake Timiskaming narrows just south of Ville-Marie, Québec (Fig. 76.10). The faulting may be related to seismic shocks, movements in the underlying bedrock, differential compaction, or rotational slumping caused by normal subaerial slope processes. Although the known high level of seismic activity in the region would favour a tectonic origin for these features, until more profiling is carried out in the southern part of the lake, their relationship to seismicity must be regarded as tentative.

CONCLUSION

Sonar profiling with portable, high-resolution, low-frequency acoustic equipment has revealed the effects of a documented earthquake and has documented other bottom and subbottom features thought to be related to seismic or tectonic activity that occurred after the last glaciation. Evidence for neotectonic or paleoseismic activity comprises two groups of features: 1) Seismicity is suggested by slumping and mudflow of both gyttja and fine grained elastic sediments. 2) Postglacial neotectonism or tilting, apparently unrelated to glacioisostatic adjustments, is suggested both by faulting of lacustrine sediments in response to differential movements of their underlying bedrock floor and by the "drowned" appearance of fluvial features that were clearly formed by active fluvial erosion since the last glaciation, but are now submerged in a lake. Caution must be exercised in the interpretation of similar-appearing features, however, because many lake basins contain sediments deformed or faulted as a result of their postdepositional collapse over buried, melting remnants of glacier ice. Slumping also can be induced by nonseismic processes related to sedimentation on steep, subaqueous slopes. A clear differentiation among these types of triggering mechanisms for sediment disturbance can only be made with any degree of certainty where the youngest postglacial sediments are clearly disturbed by the deforming process and the glacial history and late glacial and postglacial sedimentology of the lake basin is understood.
ACKNOWLEDGMENTS

The author was capably assisted in the field by A. Larocque and L. Farrell. The manuscript benefited from discussions with R.N.W. DiLabio and critical reading by J.E. Adams and J.J. Veillette. The author assumes full responsibility for conclusions drawn.

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for reference in public libraries across Canada

Cat. No. M44-84/1AE Canada: $15.00
ISBN 0-660-11531-X Other countries: $18.00

Price subject to change without notice

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Left: Perched erratic boulder near Cape Herschel, Ellesmere Island, N.W.T. (GSC 203670-U)
Right: Conducting experimental induced polarization measurements in the GSCs 300 metre test borehole at Bells Corners near Ottawa. (GSC 203575-P)