A POSSIBLE TSUNAMI IN THE LABRADOR SEA RELATED TO THE DRAINAGE OF GLACIAL LAKE AGASSIZ ~8400 YEARS B.P.

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ABSTRACT

For thousands of years, the thick Laurentide Ice Sheet covered a large part of northern North America, damming northward-draining rivers. As this ice retreated, large lakes formed along its margin. Glacial Lake Agassiz was the largest of these ice-marginal lakes, covering an area of >800,000 km^2 (more than twice the size of the largest lake in the modern world, the Caspian Sea) before it drained catastrophically into the Labrador Sea. Even before that, Lake Agassiz had periodically released large volumes of water into the ocean via the Great Lakes-St. Lawrence and the Athabasca-Mackenzie River systems. The last and largest of these outbursts released >150,000 km^3 through Hudson Bay and Hudson Strait in 6-12 months; the average flux over that period was ~5 Sv (1 Sv = 1×10^6 m^{3}s^{-1}).

When a volume of water this large is discharged into a coastal sea like the Labrador Sea, it may generate a surface flood wave or a tsunami if the water mass is large enough and introduced in a short time. To our knowledge no previous calculations have been made to estimate the potential impact of a flood burst on the generation of solitary waves. Using analogies of tsunamis generated by submarine landslides and ocean earthquakes, the amplitude of a Lake Agassiz generated tsunami is estimated to have been at least 2 m. Directionality considerations, as well as the effect of the Coriolis Force in the Northern Hemisphere, suggest that the resulting tsunami probably traveled 50-100 km along the west coast of the Labrador Sea, south of Hudson Strait where the outburst entered the ocean, before being dissipated. The erosional and depositional affects of historic and prehistoric tsunamis are present in the geological record, and provide guidance in seeking evidence for the Lake Agassiz flood burst and subsequent tsunami. This record may be found along the western coast of the Labrador Sea as well as along the shores of Hudson Strait.

1. INTRODUCTION

There are several sources for tsunami generation: submarine earthquakes which displace segments of the earth's crust, submarine volcanic explosions, submarine landslides, nuclear and large-scale chemical or munition explosions in water such as the Halifax explosion in 1917 (Greenberg et al., 1993, 1994; Ruffman et al., 1995, Mader, 2004; Murty 2003; Murty et al., 2005), cosmic body strikes in the ocean, and decomposition of gas hydrate where crystallized methane and water in ocean sediment may be released when destabilized (Kennett et al., 2003). To this list of triggers, we may also add large-scale abrupt releases of water from the continent that were stored in ice-marginal lakes, although tsunami generation from this source has never been reported in the literature to the best of our knowledge.

It is known that tsunamis generated by asteroid strikes, submarine earthquakes, and volcanic explosions can travel across trans-oceanic distances, whereas those generated by chemical/munition explosions and submarine landslides are dissipated in relatively short travel distances (Murty, 1977, 2003). Our expectation is that a tsunamis generated from a sudden introduction of a large volume of water will be somewhat similar to a tsunamis from a submarine landslide or explosion, at least as far as travel distances and directionality of tsunami energy are concerned. Here, we report and discuss the possibility of tsunami generation ~8400 years ago by the abrupt (catastrophic) drainage of glacial Lake Agassiz in Canada through Hudson Strait into the Labrador Sea.

2. THE SETTING

At the end of the last Ice Age, the Laurentide Ice Sheet (see Figs. 1 and 2), which at one time had a thickness of 3 km over Hudson Bay, disintegrated rapidly. Because the ice sheet had been a barrier to normal northward drainage from a large part of North America, a fringe of ice-marginal lakes formed along the southern side of this continental ice sheet. Lake Agassiz was the largest of these lakes (Fig. 1), expanding north as the ice retreated and growing to a size of 841,000 km^2 by about 8400 years B.P. (Teller et al., 2002); this is twice the size of the Caspian Sea which is the largest lake in the modern world. Overflow from Lake Agassiz during the previous 5000 years of its life had been variously routed south through the Mississippi River to the Gulf of Mexico, east into the Great Lakes and St. Lawrence to the North Atlantic Ocean, and northwest through the Athabasca-Mackenzie rivers to the Arctic Ocean (Fig. 1) (Teller et al., 2002; Teller and Leverington, 2004). These routings of overflow had abruptly shifted from one ocean to another, and were preceded by outbursts due to lake-draw down on more than a dozen occasions (Leverington et al., 2000, 2002; Teller and Leverington, 2004). These draw-downs occurred because as the ice margin retreated it periodically uncovered lower-elevation outlets, which resulted in outbursts of 1600-9500 km^3 that lasted for a few months; this is a short-term flux of 0.05-0.03 Sv ($1 \times \text{Sv} = 1\ 10^6\ \text{m}^3\text{s}^{-1}$) (Teller et al., 2002). By 8400 years B.P., Lake Agassiz had reached a size of 841,000 km^2, with a volume of >150,000 km^3 (Teller et al., 2002; Clarke et al., 2003, 2004). Shortly after this, the glacial barrier across Hudson Bay no longer was able to retain the impounded waters of Lake Agassiz, and it drained through Hudson Bay and Hudson Strait to the Labrador Sea (Fig. 3) (Barber et al., 1999). Teller et al. (2002) estimate that Lake Agassiz drained in less than a year. Based on glaciological modelling, Clarke et al. (2004) calculated that this drainage would have taken only about 6 months. This is a flux of about 5 Sv.

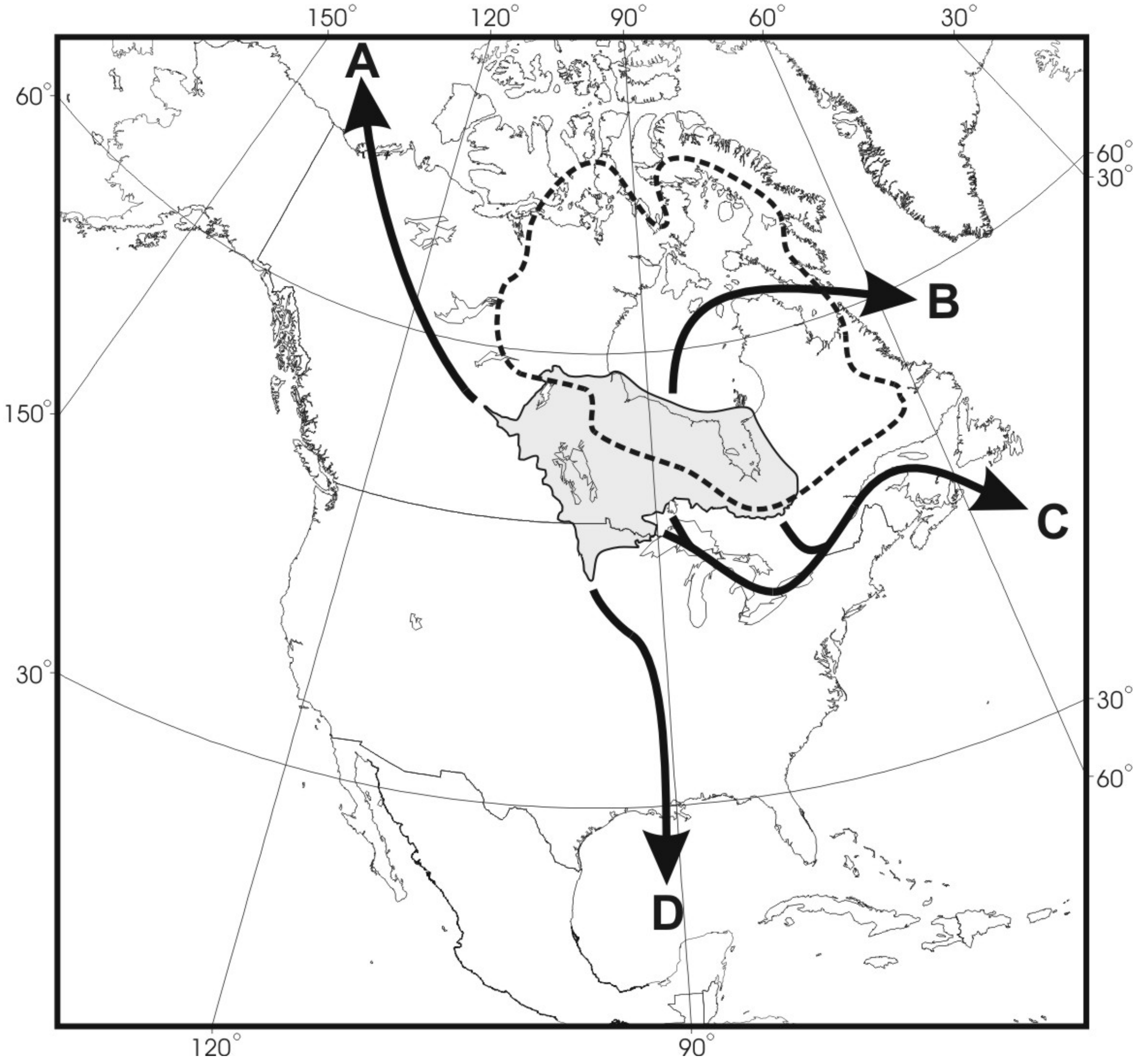

Figure 1: Map showing the total area ever covered by glacial Lake Agassiz (shaded) and the routes of overflow from this lake at various times. A = Mackenzie Valley to Arctic Ocean, B = Hudson Bay to Labrador Sea, C = St. Lawrence Valley to North Atlantic Ocean, D = Mississippi River Valley to Gulf of Mexico. Note that the final drainage of Lake Agassiz occurred along route B at ~8400 yrs B.P. The general outline of the Laurentide Ice Sheet shortly before this at 9000 yrs B.P. is shown by dashed line (Teller et al., 2002, Fig. 1, with permission of Quaternary Science Reviews and Elsevier Ltd.).

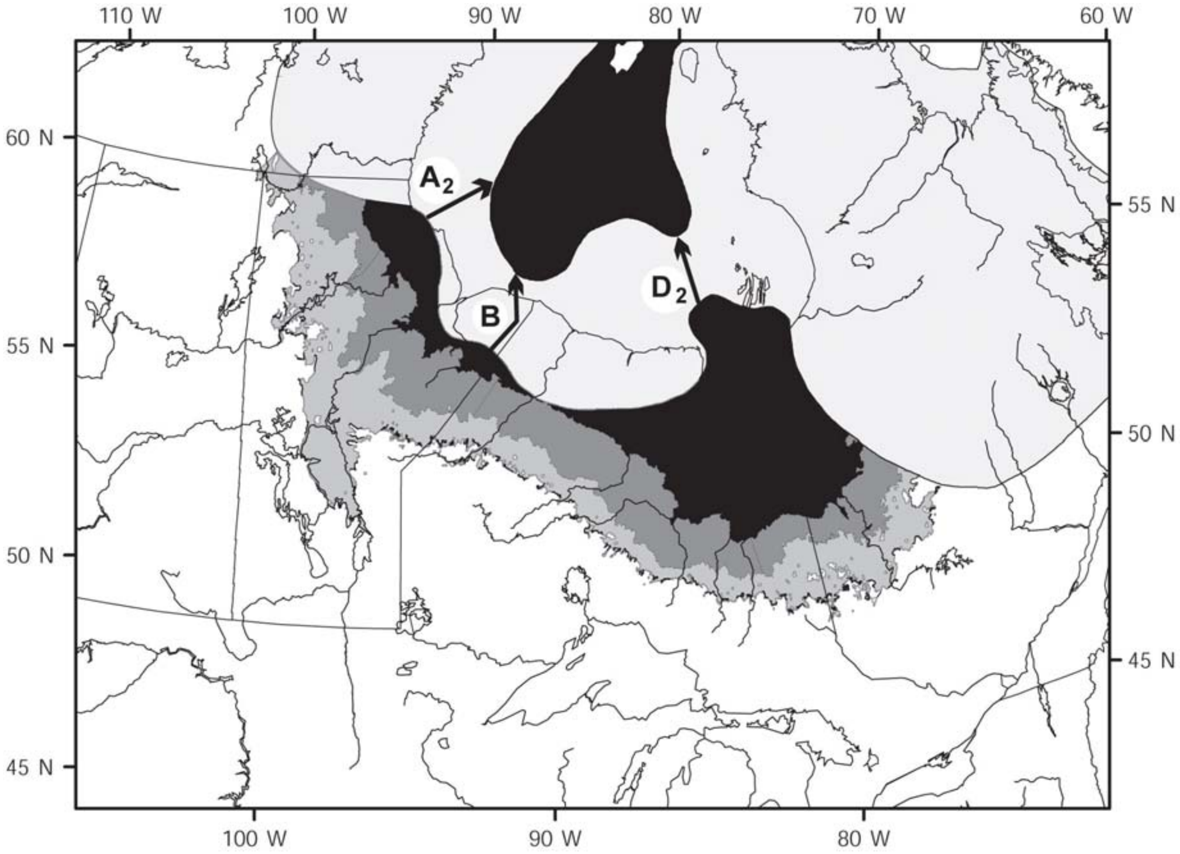

Figure 2. Area covered by Lake Agassiz ~8400 yrs. B.P., showing possible routes into Hudson Bay used by final drainage of lake (A_2, B, D_2), as explained by Clarke et al., (2004). Lightest grey area in northern region is the Laurentide Ice Sheet. Black is the area below sea level (both in Hudson Bay basin and in Lake Agassiz). The two medium grey areas along the southern side of the ice sheet are two areas covered by the lake at two stages during its drainage (Clarke et al., 2004, Fig. 3, with permission of Quaternary Science Reviews and Elsevier Ltd.).

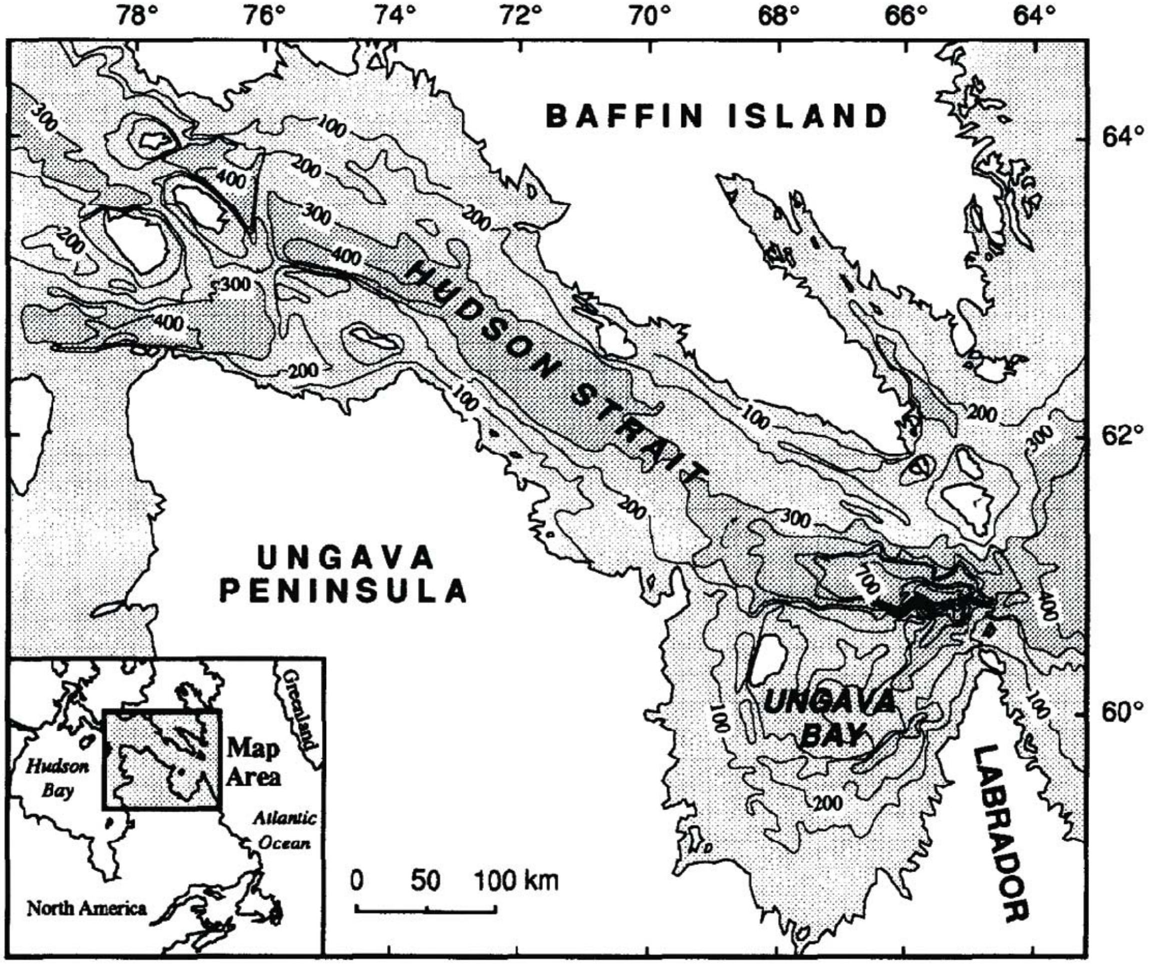

Figure 3. Modern bathymetry of Hudson Strait (Andrews et al., 1995, Fig. 1). Sea level would have been lower, but the land's surface at 8400 yrs. B.P. would have been depressed by isostasy (with permission of Quaternary Science Reviews and Elsevier Ltd.).

3. ESTIMATION OF THE TSUNAMI AMPLITUDE

We used two different methods to estimate the amplitude of a tsunami that could have been generated from the largest outburst (final drainage) from Lake Agassiz, which was about 150,000 km^3. Following Murty (2003), we used the analogy of a submarine landslide as the source for generating a tsunami, where

$$H = 0.3945\ V \tag{1}$$

H = Amplitude of tsunami in meters
V = Landslide volume that imparts impulsive momentum (millions of cubic meters)

If we take the total volume of water discharged as 150,000 km^3 and take a conservative value of one year duration for the discharge, the rate of discharge works out to be 4.76×10^6 m^3/sec or 4.76 Sv. If we use this value for V in Equation (1) we get,

H = 1.88 m

However, submarine landslides usually do not happen in just one second, they take at least 5 to 8 seconds, so V is larger. Because generation of this hyperbolic wave (tsunami) requires an impulsive addition of water, a larger duration will not contribute to this solitary (deep) wave, although it may induce a continuing, shallow, flood wave. For a 5 second duration, we multiply by 5, and H ~ 9.4 m; for an 8 second duration, H ~ 8 x 1.88 = 15 m.

In the second method, we use the analogy for tsunami generation from ocean bottom earthquakes. During the earthquake, a large mound of water instantaneously appears at the ocean surface (above the epicentral area) and this mound of water will then spread, travel, undergo dispersion and scattering (by topography), and ultimately be dissipated.

Using a rough estimate for the cross-sectional area of Hudson Strait and the average depth at its mouth ~8400 years B.P., where the average channel width was ~100 km and the depth was ~0.2 km (Fig. 3), the cross sectional area of a slug of freshwater (A) would have been 2×10^7 m^2. Murty (1979, 2003) designed a formula to estimate the height of a tsunami generated by an earthquake displacing an area of sea floor (A) having a displacive volume of V, where

$$H = \frac{V}{A} \qquad (2)$$

By using this analogy, assuming the triggering duration was 5 seconds, the tsunami amplitude (H) for the 4.76 Sv outburst (V) from Lake Agassiz was:

$V = 4.76 \text{ Sv} \times 5 \text{ seconds} = 23.8 \times 10^6 \text{ m}^3$, and

from Equation (2) we get

$$H = \frac{23.8 \times 10^6}{2 \times 10^7} = 1.19 \text{ m}$$

If we use an 8 second duration for the earthquake (Agassiz outburst), the tsunami amplitude would be about 3.8 m. If the width of Hudson Strait at its mouth is taken as 50 km instead of 100 km, then the tsunami amplitudes given above would double. If the average depth of freshwater passing through Hudson Strait near its mouth was less than the 200 m used above, then the tsunami amplitude would be greater.

In summary, it is quite likely that the amplitude of the tsunami was not less than 2 m, and could have been 5-10 m or more.

4. DIRECTIONALITY OF THE TSUNAMI ENERGY

Iwasaki (1997) studied the wave forms and the directivity of a tsunami generated by an under-ocean earthquake, as well as by a submarine landslide. He stated that landslide tsunamis show strong directivity as compared to those generated by earthquakes. However, in the quadrant of up to $3\pi/8$ from the axis of Hudson Strait, tsunami directivities are the same whether they are generated by a landslide or an earthquake and, according to the above author, in this quadrant the amplitudes of the first crest and first trough will be about equal in value.

However, for a direction greater than $3\pi/8$, the amplitude of the second crest or trough is somewhere between 1 and 1/5 of the amplitude of the first crest or trough. This means for a direction of $3\pi/8$ (i.e. 67.5°) from the minor axis (perpendicular to the initial major axis of Hudson Strait) the tsunami will dissipate rather quickly and will not travel very far.

The Coriolis Force in the Northern Hemisphere also will give this tsunami a tendency to turn to the right. By doing so, the tsunami will hug the west coast of the Labrador Sea as it travels southward. We estimate that the tsunami will travel southward along the west coast of the Labrador Sea and probably will be dissipated within a distance of about 100 km.

Considering the fact that this tsunami is expected to have an amplitude of at least 2 m, and possibly much greater, and taking into consideration the fact that it hugs the coast as it travels, there is a possibility that tsunami deposits may be found along the coast for up to 100 km.

Figure 4. Location of possible tsunami deposits associated with Lake Agassiz outburst 8400 years ago.

5. GEOLOGICAL RECORDS OF PAST TSUNAMIS

Clearly, a large ocean wave washing up on to the land will impact on the sediment cover along the coast, as well as on life. As shown by the recent tsunami in the Indian Ocean, emanating from Banda Aceh in Indonesia, as well as from other historic tsunamis, erosion and, in turn, deposition are widespread. Fine to coarse debris, at times including boulders, peat masses, trees, uprooted vegetation, and man-made materials, can be moved by the force and runup of a tsunami, and Dawson (1996) summarizes and describes (with photos) some of the changes brought about by tsunamis in historic time, such as those on Hokkaido, Japan (1993), Flores, Indonesia (1992), Lisbon (1775), and Cornwall, England (1755). In the Caribbean, Scheffers (2004) describes extensive rubble ridges, ramparts, and boulder fields deposited up to 12 m above sea level and 400 m inland, which he attributes in part to the historical record of 88 tsunamis in the region since 1489, although some of these deposits probably are related to much older events. Bondevik et al. (2005) describe evidence on the Shetland Islands for three large tsunamis in the North Sea between 8000 and 1500 years ago.

Dawson (1996, 1999), and references therein, elaborates on the nature of tsunami deposits, and Dawson (2000) and Smith et al. (2004) provide particularly informative descriptions of the stratigraphy and extent of paleo-tsunami deposits. Tidal marshes of the west coast of Canada were investigated for evidence of past tsunamis by Clague (1997), Clague et al. (1999), and Clague and Bobrowsky (1994), where the normal sedimentary sequence is interrupted by massive sheets of sand containing marine organisms and vegetal detritus; these deposits are widespread and range from a few millimetres to 0.3 m in thickness. Atwater (1987), Atwater and Moore (1992), and Darienzo and Peterson (1990) find similar sand sheets a kilometre or so inland along the Pacific Northwest of the U.S. that they relate to past tsunamis. Moore and Moore (1984, 1988) describe three sedimentary units – 2, 4, and 2 m thick – deposited during the last interglacial period by successive waves within a tsunami wave train that hit the island of Molokai in Hawaii (see Dawson, 1999). This tsunami is interpreted by Young and Bryant (1992) to have had a 20 m runup and to have eroded large blocks of bedrock as far south as the Australian coast. All these deposits have been attributed to earthquake-generated tsunamis.

In general, the considerable distance inland of coastal sand sheets attributable to paleo-tsunamis distinguishes them from those related to storm surges and hurricanes (Dawson, 1999). In addition, studies of tsunami sheet sand deposits show that they are typically graded upward, from pebbly very coarse sand to finer sand, with an inland decrease in grain size and thickness (e.g. Smith et al., 2004). The discontinuous record of the inland extent of erosion and deposition of past tsunamis make precise estimates of runup uncertain and, in turn, their amplitude imprecise (Dawson, 1999).

In contrast to seismically-induced tsunamis, submarine landslides generate a different type of wave and, therefore, impact somewhat differently on coastal areas. Specifically, tsunamis generated by submarine landslides cannot travel trans-oceanic distances as can earthquake-generated tsunamis, because their wavelengths and periods are much smaller (Murty, 1977). The well-studied Storegga submarine landslide along the Norwegian Sea coast (e.g. Dawson et al., 1988; Dawson et al., 1991; Dawson and Smith, 2000) is estimated to have occurred around 7300 ^{14}C years ago (8150 calendar yrs B.P.) (Bondevik et al., 2003; 2005), although there is a range of dates related to this event between ca. 7800 and 8400 calendar years B.P. (Smith et al., 2004). Deposits left by this tsunami are found at dozens of locations, including 250 borehole sites on the northeastern coast of the U.K., the Shetland Islands, Norway, and Iceland, and Smith et al. (2004) present a summary of the records of the tsunami beds at all these sites. Again, the tsunami deposited widespread sands up to 40 cm thick, in places containing pebbles, cobbles, and boulders as large as 25 cm, and the unit contains marine organisms, eroded peat, vegetation, and clasts ripped-up from coastal sediments; in places, the sand overlies an erosional surface in coastal lowlands and lake basins. The extent of these deposits indicates a wave runup of 10-12 m above sea level in Norway and 20 m on the Shetland Islands (Bondevik et al., 2003, 2005). Henry and Murty (1993) used a two-dimensional finite difference model to simulate the propagation of the tsunami from the Storegga landslide, estimating that the amplitude of the tsunami at the source was 8-12 m, which led to a wave height along the coast of Scotland of 2.4-5.5 m. Harbitz (1992) modelled runup heights of 1-18 m for the northern coast of Scotland, noting that local topographic effects, such as in a narrow embayment, will amplify "open-coast" numbers. Tidal factors are also likely to affect the runup of a tsunami (Smith et al., 2004).

The rough coincidence in time of the Lake Agassiz outburst and the tsunami caused by the Storegga submarine landslide prompts us to ask if that landslide could have been triggered by the Agassiz tsunami – i.e., Lake Agassiz outburst→tsunami→Storegga landslide→tsunami.

6. SUMMARY AND CONCLUSIONS

It is possible that the largest outburst from glacial Lake Agassiz through Hudson Strait into the Labrador Sea ~8400 years B.P. could have generated a tsunami. The total volume of this outburst was >150,000 km^3 and had a flux of ~5 Sv lasting 6-12 months. A field study to locate the possible deposits from this tsunami along the west coast of the Labrador Sea might provide added support for this. While an accurate estimation of the tsunami amplitude is not possible, two different analogies, one based on a submarine landslide and the other on earthquake-displacement of the seafloor, were used to arrive at an approximate value. These analogies suggest that the tsunami amplitude was not less than 2 m and probably was >5 m.

Once the Lake Agassiz outburst flood exited Hudson Strait, we would expect the resultant tsunami to turn south along the Labrador coast due to Coriolis force, just as modern runoff does today (Khatiwala et al., 1999). Although tsunami deposits and erosional features related to this event have not been identified, they are likely to be found for at least 50-100 km south of Hudson Strait, but well above sea level today. The combination of isostatic rebound and the post-glacial rise in sea level mean that the shoreline features along the Labrador coast that formed 8400 years ago now stand 20-50 m above modern sea level; this paleo-shoreline elevation would be closer to +20 m near Hudson Strait (ca. 60° N) and St. John's Newfoundland (ca. 48° N), whereas the ancient shore and its tsunami deposits would lie closer to +50 m in the region between these areas (Dyke, 1996). In addition, the effects of the continuing (6-12 month) outburst of Lake Agassiz (flood wave) along this coast may also be recorded by a scoured zone along the modern inner shelf of the Labrador Sea, or as a residual lag of coarser sediment.

REFERENCES

Andrews, J.T., McLean, B., Kerwin, M., Manley, W., Jennings, A., and Kalls, E. (1995). Final stages of the collapse of the Laurentide Ice Sheet, Hudson Strait, Canada: ^{14}C AMS dates, seismic stratigraphy, and magnetic susceptibility logs. *Quaternary Science Reviews* 14, 983-1004.

Atwater, B.F. (1987). Evidence for Great Holocene earthquakes along the outer coast of Washington State. *Science* 236, 942-944.

Atwater, B.F. and Moore, A.L. (1992). A tsunami about 1000 years ago in Puget Sound, Washington: *Science* 258, 1614-1623.

Barber, D.C., A. Dyke, C. Hillaire-Marcel, A.E. Jennings, J.T. Andres, M. W. Kervin, G. Bilodeau, R. McNeely, J. Southen, M.D. Morehead, and J.M. Gagnon (1999). Forcing of the Cold Event of 8,200 years ago by catastrophic drainage of Laurentide lakes, *Nature*, Vol. 400, 344-348.

Bondevik, S., Mangerud, J., Dawson, S., Dawson, A., and Lohne, O.(2003). Recordbreaking height for 8000-year-old tsunami in the North Atlantic: EOS, Transactions, *American Geophysical Union*, Vol. 84, No. 31, 289, 293.

Bondevik, S., Mangerud, J., Dawson, S., Dawson, A., and Lohne, O. (2005). Evidence for three North Sea tsunamis at the Shetland Islands between 8000 and 1500 years ago: *Quaternary Science Reviews* 24, 1757-1775.

Clague, J.J. and Bobrowsky, P.T. (1994). Evidence for a large earthquake and tsunami 100-400 yeas ago on western Vancouver Island, British Columbia. *Quaternary Research* 41, 176-184.

Clague, J.J. (1997): Evidence for large earthquakes at the Cascadia subduction zone: *Rev. Geophysics* 35, 439-460.

Clague, J.J., Hutchinson, I., Mathewes, R.W., and Patterson, R.T. (1999). Evidence for Late Holocene tsunamis at Catala Lake, British Columbia: *Journal of Coastal Research* 15, 45-60.

Clarke, G.K.C., D.W. Leverington, J.T. Teller and A.S. Dyke (2003). Superlakes, megafloods, and abrupt climate change. *Science* 301, 922-923.

Clarke, G.K.C., D.W. Leverington, J.T. Teller, and A.S. Dyke (2004). Paleohydraulics of the last outburst flood from glacial Lake Agassiz and the 8,200 B.P. cold event, *Quaternary Science Reviews* 213, 289-407.

Darienzo, M.E. and Peterson, C.D. (1990). Episodic tectonic subsidence of Late Holocence salt marches, northern Oregon, central Cascadia margin. *Tectonics* 9, 1-22.

Dawson, A.G., Foster, I.D.L., Shi, S., Smith, D.E., Long, D. (1991). The identification of tsunami deposits in coastal sediment sequences. *Science of Tsunami Hazards*, 9, 73-82.

Dawson, A.G. (1996). The geological significance of tsunamis. *Zeitschrift fur Geomorphologie,* N.F., Suppl. Bd. 102, 199-210.

Dawson, A.G. (1999). Linking tsunami deposits, submarine slides and offshore earthquakes. *Quaternary International* 60, 119-126.

Dawson, S. and Smith, D.E. (2000): The sedimentology of middle Holocene tsunami facies in northern Sutherland, Scotland, UK. *Marine Geology*, 170, 69-79.

Dawson, A.G. (2000). Tsunami deposits. *Pure and Applied Geophysics*, 157, 875-897.

Dyke, A.S. (1996). Preliminary paleogeographic maps of glaciated North America. *Geological Survey of Canada*, Open File 3296.

Greenberg, D.A., T.S. Murty, and A. Ruffman (1993). A numerical model for the Halifax harbour tsunami due to the 1917 explosion, *Marine Geodesy* 16, No. 2, 153-168.

Greenberg, D.A., T.S. Murty, and A. Ruffman (1994). Modelling the tsunami from the 1917 Halifax harbour explosion, *Science of Tsunami hazards* 11, No. 2, 67-80.

Harbiz, C.B. (1992). Model simulatins of tsunamis generated by the Storegga Slides. *Marine Geology* 105, 1-21.

Henry, R.F. and T.S. Murty (1993). Model studies of the effects of the Storegga slide tsunami. *Science of Tsunami Hazards* 10, No. 1, 51-62.

Iwasaki, S.I. (1997). The waveforms and directivity of a tsunami generated by and earthquake and a landslide, *Science of Tsunami Hazards*, 15, No. 1, 23-40.

Kennet, J.P., Cannariato, K.G., Hendy, I.L., Behl, R.J. (2003). Methane hydrates in Quaternary climate change. American Geophysical Union, Washington, 216 p.

Khatiwala, S.P., Fairbanks, R.G., Houghton, R. W. (1999). Freshwater sources to the coastal ocean off northeastern North America: evidence from $H_2{}^{18}O/H_2{}^{16}O$. *Journal Geophysical Research*, 104, C8, 18, 241-18, 255.

Leverington, D.W., Mann, J.D., Teller, J.T. (2000). Changes in the bathymetry and volume of glacial Lake Agassiz between 11,000 and 9300 ^{14}C yr B.P. *Quaternary Research* 54, 174-181.

Leverington, D.W., Mann, J.D., Teller, J.T. (2002). Changes in the bathymetry and volume of glacial Lake Agassiz between 9200 and 7600 ^{14}C yr B.P. *Quaternary Research* 57, 244-252.

Mader, C.L. (2004). Numerical modelling of water waves, second edition, CRC Press, Boca Raton, Florida.

Moore, J.G. and Moore, G.W. (1984). Deposit from a giant wave on the island of Lanai, Hawaii. *Science* 226, 1312-1315.

Moore, G.W., and Moore, J.G., (1988). Large-scale bedforms in boulder gravel produced by giant waves in Hawaii: *In* Sedimentologic Consequences of Convulsive Geologic Events (Clifton, H.E., ed.), *Geological Society of America Special Paper* 229, 101-110.

Murty, T.S., (1977). Seismic Sea waves-Tsunamis, Bulletin number 198, Fisheries Research Board of Canada, Ottawa, 337 Pages

Murty T.S. (1979). Submarine slide-generated water waves in Kitimat Inlet, British Columbia, *Journal of Geophysical Research*, Vol. 84, No. C12, 7777-7779.

Murty, T.S. (2003). Tsunami wave height dependence on landslide volume, *Pure and Applied Geophysics*, 160, 1-7.

Murty T.S., N. Nirupama, I. Nistor and S. Hamdi (2005). Why the Atlantic Generally cannot Generate Trans-Oceanic Tsunamis, Indian Journal of Earthquake Engineering (In Press)

Ruffman, A., D.A. Greenberg and T.S. Murty (1995). The tsunami from the explosion in Halifax harbour. *In* “Ground zero”. 327-344, Ed: A. Ruffman and C.D. Howell, Nimbus Publishing Ltd., Halifax.

Scheffers, A. (2004). Tsunami imprints on the Leeward Netherlands Antilles (Aruba), Curacao, Bonaire) and their relation to other coastal problems: *Quaternary International* 120, 163-172.

Smith, D.E., Shi, S., Cullingford, R., Dawson, A., Dawson, S., Firth, C., Foster, I., Fretwell, P., Haggart, B., Holloway, L., and Long, D. (2004). The Holocene Storegga Slide tsunami in the United Kingdom. *Quaternary Science Reviews* 23, 2291-2321.

Teller, J.T., D.W. Leverington and J.D. Mann (2002). Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in climate change during the last deglaciation, *Quaternary Science Reviews*, 21, 879-887.

Teller, J.T. and D.W. Leverington (2004). Glacial Lake Agassiz: A 5,000 year history of change and its relationship to the δ^{18}o record of Greenland. *Geological Society of America Bulletin*, 116, 729-742.

Young, R.W., and Bryant, T. (1992). Catastrophic wave erosion on the southeastern coast of Australia: impact of the Lanai tsunami ca. 105 ka? *Geology* 20, 199-202.